

摘要

沿海高密度街区的行人风环境直接关乎公共空间安全与宜居。台风与强阵风频发背景下，高层高密度开发易诱发狭管效应、角隅流及下洗气流，放大局部风速，严重威胁行人安全。现有评估多聚焦宏观气象，在设计阶段缺少对微观形态隐患的快速筛查手段；传统 CFD 模拟虽精度高，但计算消耗大、周期长，难以适应方案快速迭代。为此，本研究构建了基于城市形态参数的快速评估模型，旨在量化空间形态与行人风速的耦合关系，为气候响应性设计提供高效决策支持。以香港旺角高密度街区为例，结合 GIS 参数化提取与并行化大涡城市应用模型（PLAM-4U）进行大涡模拟，从建筑实体与开放空间两维度建立 11 项形态参数指标，在 30~150 m 的 5 个观测尺度上采集 7161 个样本的风速与形态数据；采用斯皮尔曼相关分析和多元线性回归解析参数影响机理，并利用随机森林与 XGBoost 算法构建风环境风险快速预测模型。结果表明，所选形态参数对行人风环境解释力较强，且呈现显著的尺度分异：建筑阻挡类参数在小尺度关联最强，反映局部机械阻碍效应；空间连通度与暴露程度参数则在大尺度效应最突出。随机森林经 5 折交叉验证，对三级风风险分类准确率达 76.7%可脱离复杂数值模拟实现风险快速预判。基于机器学习分析生成设计导则，并针对城市更新的可实施性与改造迫切性，将优化导则实证应用于香港马头角更新片区进行方案示意。理论上，本研究深化了高密度形态与近地面微气候的定量耦合认知，推动风环境从定性描述转向定量预测；实践上，快速评估模型降低了技术门槛与时间成本，使气候响应性设计能够融入更新前期决策。所得优化策略可有效规避局部强风、提升空间韧性，为沿海高密度城市的科学规划与精细化管控提供了可行路径。

关键词：城市风环境；行人高度风环境；沿海高密度街区；城市形态参数；气候响应性设计

Abstract

Pedestrian wind environment in high-density coastal districts is directly linked to public-space safety and livability. Under the frequent impact of typhoons and strong gusts, high-rise, high-density developments easily induce venturi effects, corner flows and downwash, which amplify local wind speeds and seriously threaten pedestrian safety. Existing assessments mainly focus on macro-scale meteorology and still lack rapid screening tools to identify micro-scale morphological hazards at the design stage. Although traditional CFD simulations offer high accuracy, their heavy computational cost and long turnaround time make them unsuitable for fast design iteration. To address this gap, this study constructs a rapid assessment model based on urban morphological parameters, aiming to quantify the coupling between spatial form and pedestrian-level wind speed and to provide efficient decision support for climate-responsive design. Taking the high-density Mong Kok district in Hong Kong as a case, GIS-based parametric extraction and the Parallelized Large-eddy Simulation Model for Urban Application (PLAM-4U) are combined to perform large-eddy simulations. Eleven morphological parameters are established from two dimensions—building mass and open space—and wind-speed and morphology data are collected from 7,161 samples across five observation scales (30–150 m). Spearman correlation analysis and multiple linear regression are employed to reveal parameter influence mechanisms, while Random Forest and XGBoost algorithms are used to build a rapid wind-risk prediction model. Results show that the selected morphological parameters have strong explanatory power for pedestrian wind environment and exhibit marked scale differentiation: building obstruction parameters correlate most strongly at small scales, reflecting local mechanical blocking effects, whereas parameters describing spatial connectivity and exposure dominate at larger scales. With 5-fold cross-validation, the Random Forest model achieves a three-class wind-risk classification accuracy of 76.7%, enabling rapid risk pre-screening without complex numerical simulations. Design guidelines are derived from the machine-learning analysis. Considering the implementability and urgency of

urban renewal, the optimization guidelines are empirically applied to the Ma Tau Kok renewal area in Hong Kong as a schematic illustration. Theoretically, this study deepens the quantitative understanding of the coupling between high-density urban form and near-ground microclimate, advancing wind environment assessment from qualitative description to quantitative prediction. Practically, the rapid assessment model lowers technical barriers and time costs, allowing climate-responsive design to be integrated into early-stage renewal decisions. The resulting optimization strategies can effectively avoid localized strong winds and enhance spatial resilience, offering a feasible pathway for science-based planning and fine-grained management of high-density coastal cities.

Keywords: Urban Wind Environment; Pedestrian-Level Wind Environment; Coastal High-Density Urban Blocks; Urban Morphological Parameters; Climate-Responsive

Contents

Chapter 1.Introduction	1
1.1 Research Background	1
1.1.1 Pedestrian level wind environment Issues in High-Density Coastal Neighborhoods	1
1.1.2 Limitations of Field Measurement and Simulation in Urban Wind Environment Studies	3
1.1.3 The Relationship Between Urban Form and Pedestrian level wind environment	6
1.2 Research Objectives and Significance	9
1.2.1 Research Objectives	9
1.2.2 Research Significance	10
1.3 Conceptual Definition	11
1.3.1 Block Scale	11
1.3.2 Coastal high-density blocks	12
1.3.3 Urban Morphological Parameters	15
1.3.4 Pedestrian-Level Wind Environment Assessment	16
1.4 Research Review	17
1.4.1 History and Development of Related Research	17
1.4.2 Methods for Urban Pedestrian level wind environment Assessment	19
1.4.3 Shortcomings and Limitations of Existing Research	22
1.5 Research Content and Methods	22
1.5.1 Research Content	22
1.5.2 Research Methods	25
1.6 Research Framework	27
Chapter 2.Construction and Research of the Urban Morphological Parameter Database	28
2.1 Definition of Urban Morphological Parameters	28

2.1.1 Building Morphological Parameters	31
2.1.2 Open Space Morphological Parameters	34
2.2 Calculation of Urban Form Parameters	36
2.2.1 Study Area	36
2.2.2 Data Preprocessing	38
2.2.3 Extraction of Open Centerlines	40
2.2.4 Calculation and Analysis of Urban Morphological Parameters	42
2.3 Summary of This Chapter	44
Chapter 3.PALM-4U Simulation Setup and Evaluation Metrics	47
3.1 PALM-4U Model Overview and Applicability Analysis	48
3.1.1 Basic Principles of Large-Scale Turbulence Simulation	48
3.1.2 PALM-4U Model Architecture and Features	49
3.1.3 Analysis of the Applicability of Large Eddy Simulation (LES) in Pedestrian level wind environment Assessments	51
3.2 Wind Tunnel Experimental Reference Data	53
3.3 Computational Domain Construction and Mesh Generation	55
3.3.1 Construction of the Mong Kok District Geometric Model	55
3.3.2 Computational Domain Setup and Static Driver Generation	56
3.4 Boundary Conditions and Parameter Configuration	57
3.4.1 Boundary Condition Settings	57
3.4.2 Initial Conditions and Wind Profile Settings	59
3.5 Simulation Validation and Sensitivity Analysis	63
3.5.1 Wind Tunnel Experimental Reference Data	63
3.5.2 Determination of the Roughness Parameter (z_0)	64
3.5.3 Comparative Experiments with Different Inflow Configurations	64
3.6 Validation of Simulation Results	66
3.6.1 Evaluation Metrics and Validation Methods	66
3.6.2 Validation of Wind Speed at Pedestrian Height	67

3.6.3 Analysis of Simulation Deviations and Model Applicability	68
3.7 Pedestrian level wind environment Evaluation Index System	70
3.8 Summary of This Chapter	71
Chapter 4.PALM-4U Simulation Process and Results	73
4.1 Construction and Simulation of the Global Model	73
4.1.1 Overview of the Mong Kok Area-Wide Static Driver File	74
4.1.2 Generation of Static Files	75
4.1.3 PALM Urban Wind Environment Simulation Input Settings	76
4.1.4 Simulation Results	78
4.2 Overall Characteristics of the Wind Environment at Pedestrian Height	79
4.2.1 Wind Speed Distribution	79
4.2.2 Frequency Distribution Characteristics	80
4.3 Analysis of Flow Field Mechanisms in Typical High-Density Coastal Urban Settings	81
4.3.1 Spatial Distribution Characteristics of High-Wind-Speed Clusters	81
4.3.2 Discussion on Wind Speed Attenuation Mechanisms in High-Density Low-Rise Neighborhoods	82
4.3.3 Comprehensive Patterns of Urban Form's Impact on Pedestrian Wind Speed	83
4.4 Pedestrian level wind environment Risk Assessment Results	84
4.4.1 Overall Risk Level Distribution	84
4.4.2 Statistical Analysis of the Spatial Distribution of Pedestrian level wind environment Indicators	84
4.5 Summary of This Chapter	85
Chapter 5.Construction of a Rapid Prediction Model for Pedestrian Wind Environment	87
5.1 Research Data and Wind Speed Classification Standards	87
5.1.1 Sample Overview	87
5.1.2 Wind Speed Classification Criteria	87
5.2 Univariate Correlation Analysis of Urban Morphological Parameters and Wind Speed Categories	88

5.2.1 Spearman's rank correlation analysis	88
5.2.2 Comparison of Significant Parameters	89
5.2.3 Optimal Computational Scale for Each Parameter	90
5.3 Comparison of Significance Rankings for Urban Morphology Parameters via Multiple Linear Regression	92
5.3.1 Screening Method	92
5.3.2 Screening Results	93
5.3.3 Interpretation of Results	93
5.4 Development of a Pedestrian level wind environment Prediction Model Based on Random Forest and XGBoost Ensemble Learning Algorithms	95
5.4.1 Analytical Methods and Model Validation Strategies	95
5.5 Summary of This Chapter	99
Chapter 6.Proposal of Guidelines for Optimizing Urban Morphology for Pedestrian level wind environment and Examples of Morphological Remodeling	102
6.1 Comprehensive Analysis of the Impact Mechanisms of Urban Form Parameters	102
6.1.1 Ranking of Parameter Influence Directions and Intensities	102
6.1.2 The Spatial Hierarchical Significance of the Optimal Computational Scale .	104
6.2 General Guidelines for the Design of High-Density Coastal Neighborhoods Based on Pedestrian level wind environment	105
6.2.1 Coordinated Control Strategies for Floor Area Ratio (FAR) and Building Density (D)	105
6.2.2 Zoning Height Control Strategies and Form Transition Strategies for Building Height	106
6.2.3 Optimization Strategies for Wind Corridor Systems Based on Open Space Connectivity	109
6.2.4 Design Strategies for Podium Forms Based on the Podium Wind Exposure Area Index	111
6.2.5 Site Design Strategies for Building Spacing (S) and Building Coverage Ratio	

(λ b)	113
6.3 Comprehensive Guideline System and Zoning Applications	114
6.3.1 Risk-Based Zoning Control Framework	114
6.3.2 Key Implementation Points at Each Planning and Design Level	115
6.3.3 Limitations and Scope of the Guidelines	116
6.4 Example of Morphological Optimization for High-Risk Old Neighborhoods in Hong Kong Based on Pedestrian level wind environment	118
6.4.1 Study Area Overview: Ma Tau Kok District	118
6.4.2 Regional Climate Characteristics and Wind Field Background	119
6.4.3 Analysis of Potential Pedestrian level wind environment Risks in Complex Coastal Environments	120
6.4.4 Urban Renewal Design Approach for the Ma Tau Kok Coastal Area: Empirical Application of Pedestrian level wind environment Guidelines	123
6.4.5 Strategies for Reshaping the Spatial Framework and Redirecting the Road Network	123
6.4.6 Gradual Skyline Transition and Coordinated Height Control at the Macro Level	124
6.4.7 Block-Scale Podium Interventions and Interface Filling Mechanisms	126
6.4.8 Synergistic Compensation Between Enhanced Ecological Resilience and Form Control	127
6.4.9 Site plan and conceptual rendering after architectural form optimization	129
6.5 Summary of this chapter	130
Conclusion	132
Reference	136
Appendix	144

List of Figures

Figure 1-1 Urban morphology of the Mong Kok district in Hong Kong	13
Figure 1-2 Urban Form of Futian District, Shenzhen	13
Figure 1-3 Urban Form of the Lujiazui Area in Shanghai	14
Figure 1-4 Urban Form of Singapore's Marina Bay Area	14
Figure 1-5 Urban Form of the Guangzhou Zhujiang New Town Area	15
Figure 1-6: Workflow Framework	27
Figure 2-1 Pic of Mong Kok	37
Figure 2-2 Study Area	38
Figure 2-3 Building forms within the study area	39
Figure 2-4 Building centerlines within the study area	42
Figure 2-5 Schematic of the computational domain	43
Figure 2-6 Example of urban morphology parameter calculation results: Heatmap of the calculation results for parameter D ₃₀	44
Figure 3-1 Large-Eddy Simulation (LES) wind field diagram for a building	49
Figure 3-2 Introduction and Capabilities of the PALM-4U Model	51
Figure 3-3 PALM-4U model code interface	53
Figure 3-4 Wind tunnel experiments in the Mong Kok district of Hong Kong	54
Figure 3-5 Plan view of the PALM simulation model	57
Figure 3-6 PALM simulation interface	63
Figure 3-7 Comparison of the uncorrected wind profile with the wind tunnel wind profile	65
Figure 3-8 Validation of Simulation Results	67
Figure 3-9 Simulation Results	68
Figure 4-1 Overall study area and the validation area from Chapter 3	74
Figure 4-2 Urban wind field map of the Mong Kok district under strong southeasterly convective weather	78
Figure 4-3 Statistics on locations of strong winds in urban horizontal wind fields under severe	

convective weather	79
Figure 4-4 High-Risk Pedestrian level wind environment Zone A	82
Figure 4-5 High-Risk Pedestrian level wind environment Zone B	82
Figure 5-1 Comparison of training results for mainstream predictive models	97
Figure 5-2 Wind speed prediction results and error analysis for mainstream prediction models	98
Figure 5-3 Statistical Analysis of Prediction Model Training Samples	99
Figure 6-1 Schematic diagram of general urban form design strategies based on pedestrian level wind environment	106
Figure 6-2 Schematic diagram of general urban form design strategies based on pedestrian level wind environment	108
Figure 6-3 Schematic diagram of general urban form design strategies based on pedestrian level wind environment	109
Figure 6-4 Schematic diagram of general urban form design strategies based on pedestrian level wind environment	111
Figure 6-5 Schematic diagram of general design strategies for urban form based on pedestrian level wind environment	113
Figure 6-6 Schematic diagram of general design strategies for urban form based on pedestrian level wind environment	114
Figure 6-7 Site awaiting renewal in the Ma Tau Kok district, Kowloon, Hong Kong	119
Figure 6-8 Schematic diagram of Hong Kong's southeastern wind corridor	120
Figure 6-9 Example of urban form optimization based on pedestrian level wind environment for the study site	122
Figure 6-10 Current building form of the study site	122
Figure 6-11 Impact of road network configuration adjustments on the pedestrian wind environment	124
Figure 6-12 Impact of building height control on the pedestrian wind environment	126
Figure 6-13 Impact of Form Control on Pedestrian Wind Environment	127
Figure 6-14 Optimization of the wind environment and urban ecological resilience through	

rooftop greening.....	128
Figure 6-15 Wind-Safety-Based Optimization of the Matoujiao Coastal Block Form—Master Plan.....	129
Figure 6-16 Wind-Safety-Based Optimization of the Matoujiao Coastal Block Form—Aerial View	129
Figure 7-1 Statistical Distribution of Urban Morphology Parameter C	144
Figure 7-2 Statistical Distribution of Urban Form Parameter Hm	145
Figure 7-3 Statistical Distribution of Urban Form Parameter HV	145
Figure 7-4 Statistical Distribution of Urban Form Parameter FAR	146
Figure 7-5 Statistical distribution of urban form parameter D	146
Figure 7-6 Statistical Distribution of Urban Form Parameter W	147
Figure 7-7 Statistical Distribution of Urban Morphology Parameter S	148
Figure 7-8 Statistical Distribution of Urban Morphology Parameter SVF	148
Figure 7-9 Statistical Distribution of Urban Morphological Parameter FAI	149
Figure 7-10 Statistical distribution of the urban form parameter λ_b	150

Chapter 1 Introduction

1.1 Research Background

1.1.1 Pedestrian level wind environment Issues in High-Density Coastal Neighborhoods

Due to their unique geographical location, coastal cities are long-term subjects to monsoon climates and frequently experience extreme weather events such as typhoons during the summer and fall seasons. In recent years, with the intensification of global climate change, both the frequency and intensity of strong wind events have shown a marked upward trend, posing an increasingly severe threat to urban safety. According to statistical data, when Typhoon Mangkhut struck Hong Kong in 2018, it resulted in over 450 injuries and direct economic losses amounting to tens of billions of Hong Kong dollars; in 2019, Typhoon Lekima made landfall along the coast of Zhejiang, causing significant casualties and property damage. These cases clearly demonstrate that extreme wind disasters have become a major safety hazard that cannot be ignored in coastal cities.

At the same time, to address the dual pressures of population growth and limited land resources, coastal cities have generally adopted high-rise, high-density development strategies. Take Hong Kong as an example: its building density ranks among the highest globally, with high-rise buildings densely packed in the urban area and a building coverage rate exceeding 30%. Mainland coastal cities such as Shenzhen and Shanghai similarly exhibit this high-density development model. While this development model improves land use efficiency, it has also significantly altered the city's wind environment characteristics. From a macro perspective, high-rise, high-density construction effectively increases urban roughness and surface resistance, thereby reducing the overall average wind speed in the region. However, this apparent "wind-reduction" effect often masks more severe localized strong wind issues at the micro scale.

At the neighborhood level, improper building layouts can create various hazardous wind patterns. First is the "wind corridor effect": when clusters of buildings form narrow, elongated street valleys, the incoming wind is constrained by high-rise buildings on both sides, creating

a significant acceleration effect within the corridor, resulting in wind speeds at pedestrian height reaching 1.5 to 2 times or more the incoming wind speed. Second is the "downwash" phenomenon: airflow on the windward side of high-rise buildings is forced to deflect downward, creating strong downwash winds at the building base and surrounding areas, threatening pedestrian safety. Third is the "corner vortex": at building corners, airflow separation creates localized vortex zones, generating strong winds with variable and unpredictable directions. Additionally, the enclosed layout of building clusters may create "wind vortices" in internal courtyards or plazas, transforming what should be comfortable and pleasant public spaces into high-risk areas.

These localized high-wind issues directly threaten the safety of pedestrians' daily commutes and the comfort of public spaces. When wind speeds at pedestrian height exceed 5 meters per second, people experience significant discomfort; when speeds reach 10 meters per second or higher, pedestrians struggle to walk, and the elderly and children face a risk of falling; and when speeds exceed 15 meters per second, even healthy adults find it difficult to maintain their balance, making falls highly likely. Furthermore, strong winds can lead to secondary hazards such as damage to outdoor facilities, falling billboards, and broken trees, with flying debris posing a serious threat to pedestrians^[1]. During a strong wind event in Hong Kong in 2017, the wind corridor effect created by the cluster of buildings in Central caused several pedestrians to be blown over and injured, and shattered the glass of some shops, fully illustrating the real-world dangers of localized strong winds. More seriously, prolonged exposure to adverse wind conditions significantly diminishes the vitality of public spaces. As people reduce outdoor activities to avoid strong winds, public spaces such as plazas and pedestrian streets — originally designed for socializing and leisure — gradually become underutilized, ultimately eroding the quality of urban public life.

However, current planning and design practices pay insufficient attention to pedestrian level wind environment issues. During the planning and design phases of projects, wind environment assessments are often overlooked or limited to rough qualitative analyses, lacking quantitative scientific evaluation. Many wind environment problems are only

discovered after buildings are constructed and put into use — through resident complaints, on-site measurements, or extreme weather events. At this stage, rectification is not only costly but also technically extremely challenging, often leaving only temporary remedial measures as an option. The primary reason for this situation is that while traditional wind environment assessment methods offer high precision, they are characterized by high computational costs, lengthy cycles, and complex operations, making them difficult to employ frequently during the early design phase when multiple alternatives are being evaluated. Planners and designers urgently need a rapid, simple, and low-cost assessment tool capable of identifying potential pedestrian level wind environment hazards at the initial design stage, thereby preventing problems at their source. This practical need constitutes a key starting point for this study.

1.1.2 Limitations of Field Measurement and Simulation in Urban Wind Environment Studies

In current urban wind environment research and practice, field measurements and numerical simulations serve as the two mainstream methods. Although each has its own advantages in terms of accuracy and reliability, they also face unavoidable and significant limitations. These limitations severely restrict the widespread application of wind environment assessment throughout the entire planning and design process and, to some extent, have even become one of the key root causes of frequent pedestrian level wind environment issues.

First, field wind speed measurements, as a direct means of obtaining real wind environment data, are severely constrained by multiple factors such as time, space, and cost. From a temporal perspective, the urban wind environment exhibits high temporal variability and seasonal characteristics; obtaining statistically representative wind speed data often requires long-term monitoring spanning several months or even multiple years^[2]. However, in the fast-paced reality of urban development, the timeline from planning to construction is often extremely tight, making it impossible to wait for the accumulation of field data over several months. From a spatial perspective, the wind environment at the block scale exhibits high spatial heterogeneity; areas of strong winds are often confined to a range of just a few meters to several dozen meters. To comprehensively capture these fine-grained spatial

distribution characteristics, a large number of measurement points must be deployed within the block to form a dense monitoring network^[3]. Taking a typical 500-meter-by-500-meter block as an example, achieving a 50-meter grid resolution would require deploying at least 100 measurement points, resulting in extremely high equipment procurement and maintenance costs. More critically, the greatest limitation of the field measurement method lies in its inability to predict: for planning schemes that have not yet been constructed, this method is completely ineffective. Designers are forced to "design blindly and verify upon completion," making corrections only after problems are discovered. This approach is not only costly but also often misses the optimal window for intervention^[4]. It is precisely due to these fundamental flaws that the field measurement method cannot serve as a standard tool for wind environment assessment during the planning and design phase.

Second, while computational fluid dynamics (CFD) numerical simulation is the mainstream method for wind environment research today, and although it can predict wind field distributions for unbuilt proposals in a virtual environment, its relatively high technical barriers, significant computational costs, and complex operational procedures deter the vast majority of planning and design teams. CFD simulation requires users to possess specialized knowledge in fluid mechanics, numerical computation, and mesh generation. Every step—from model creation and boundary condition setting to turbulence model selection, mesh generation, and optimization—can have a decisive impact on the results; even the slightest error can lead to severe distortion of the simulation outcomes. Even for experienced CFD experts, completing a high-quality simulation at the block scale can take several weeks: geometric modeling, meshing, and optimization require 3–5 days; solving the equations on high-performance computing workstations or servers takes several days to weeks; and post-processing and result analysis require several more days^[1]. More critically, during the early stages of planning and design, it is often necessary to compare and screen multiple alternative schemes. Every adjustment to a scheme requires remodeling and recalculation; this high time and financial cost makes it difficult for CFD simulations to meet the demands of design iteration. Furthermore, CFD simulations place extremely demanding requirements on

computational resources: to ensure result accuracy, the computational domain must be sufficiently large and the mesh sufficiently dense, resulting in total mesh counts that easily reach millions or even tens of millions. Ordinary workstations are simply incapable of handling this, necessitating reliance on expensive high-performance computing clusters^[5]. These technical and economic barriers exclude the vast majority of small and medium-sized planning and design teams, resulting in wind environment assessment becoming a "luxury" rather than a "necessity" in practice.

Wind tunnel testing, as another important method of wind environment research, can intuitively reproduce real wind fields through physical models; however, its high cost, lengthy cycle, and strict requirements for testing facilities make its application extremely limited. A complete wind tunnel test requires the construction of a detailed physical model (including the target block and surrounding environment), with model construction costs typically ranging from tens of thousands to hundreds of thousands of yuan; during the test, specialized wind tunnel equipment must be rented, with hourly rental rates reaching thousands to tens of thousands of yuan; and the collection and analysis of test data require a professional team to invest a significant amount of time. Throughout the entire process, the total cost of a single wind tunnel test often exceeds hundreds of thousands of yuan, with a duration spanning several months—a burden that is simply unaffordable for the vast majority of urban renewal projects. More critically, wind tunnel testing is ill-suited to the demands of design iteration: every adjustment to the proposal necessitates the creation of a new model and a new test. This “one-time” nature prevents it from supporting the dynamic optimization process of planning and design^[6].

In summary, whether it be field testing, CFD simulation, or wind tunnel testing, the common challenges of existing methods lie in their high costs, long lead times, and high barriers to entry, making them difficult to use frequently during the early stages of planning and design or during the phase of comparing multiple design alternatives. The direct consequence of this dilemma is that wind environment assessment has been marginalized, reduced to a "formal review" or "post-hoc remedy" in the later stages of a project, rather than

serving as "upfront guidance" for design decisions. A large number of pedestrian level wind environment hazards go unrecognized during the design phase and are only exposed after construction and occupancy. At this stage, rectification is not only costly but also technically extremely challenging, often leaving only temporary remedial measures as an option. This practical dilemma highlights the extreme urgency of developing a rapid, simple, and low-cost tool for wind environment safety assessment—which is precisely the core starting point of this study.

1.1.3 The Relationship Between Urban Form and Pedestrian level wind environment

As a fundamental component of the urban physical space, urban form exerts a decisive influence on the near-surface wind environment. Urban form refers to the three-dimensional arrangement and geometric characteristics of elements such as buildings, streets, and open spaces, encompassing multiple dimensions including building height, density, volume, layout patterns, street width, and building spacing^[7]. These morphological elements directly shape the wind environment characteristics at pedestrian height by altering the path, velocity, and turbulence intensity of airflow.

From an aerodynamic perspective, complex changes in the flow field occur when wind encounters a cluster of buildings: a high-pressure zone forms on the windward side, causing the airflow to slow down; an acceleration effect occurs at the top and sides of the buildings; and a low-pressure vortex zone appears on the leeward side^[8]. In high-density urban environments, densely arranged clusters of high-rise buildings generate the "Street Canyon Effect" and the "Venturi Effect": as wind passes through narrow street canyons, it is constrained by the buildings on either side, causing flow velocity to increase significantly; meanwhile, at specific locations such as building corners and the edges of podiums, localized extreme wind speeds may arise due to airflow convergence, creating so-called "wind hazard points." Extensive empirical research indicates a significant quantitative relationship between urban morphological parameters and wind speeds at pedestrian height. Ng et al. (2011) found in their study of high-density districts in Hong Kong that for every 10% increase in building density, the average wind speed within street canyons decreases by 15%–20%, but this

simultaneously leads to wind speed increases of over 30% in local acceleration zones^[9]. Yuan et al. (2014) compared CFD simulation results for different building layout patterns and noted that a grid-like layout is more likely to form through-wind tunnels between buildings than an enclosed layout, increasing the probability of local wind speeds exceeding safety thresholds by 2–3 times^[10]. Variations in building height are also a key influencing factor: when there is a significant height difference between adjacent buildings, tall structures "push" strong high-altitude winds downward toward the ground, creating downwash, which causes a sharp increase in wind speeds at the base of the building and in the surrounding areas^[11].

The aspect ratio (H/W) of a street canyon is widely recognized as the core parameter influencing the wind environment within the canyon. When $H/W < 0.5$, airflow above the canyon can flow smoothly into the canyon interior, and the wind speed within the canyon is close to that of the incoming flow; when $0.5 < H/W < 2$, a stable vortex structure forms within the canyon, and the ground wind speed decreases significantly; whereas when $H/W > 2$, the canyon evolves into a "deep canyon," with extremely low internal wind speeds but a possible strong acceleration effect at the canyon mouth. The frontal area density of a building is equally critical: this parameter reflects the overall degree to which a building complex obstructs the incoming airflow. When it exceeds a critical threshold (typically 0.25–0.30), it triggers extensive flow separation and acceleration, leading to pedestrian level wind environment issues^[12]. Furthermore, the plan form and facade details of buildings can significantly influence local wind fields. Streamlined designs, such as rounded corners and sloped surfaces, can effectively mitigate airflow separation, reducing turbulence intensity and peak wind speeds around the building. Conversely, sharp building corners, protruding podium edges, and openings in elevated floors often act as "trigger points" for high wind speeds. In recent years, with the advancement of parametric design and computational tools, researchers have begun to attempt to establish predictive models linking urban morphological parameters to wind environment indicators, providing rapid tools for pedestrian level wind environment assessment during the design phase^[13]. In summary, urban form profoundly influences wind speed distribution and safety conditions at pedestrian heights by altering airflow paths and

energy distribution. Understanding and quantifying this relationship is a prerequisite and foundation for achieving wind-safety-oriented urban design.

In addition to building form, urban vegetation cover and topographic variations also exert significant influences on the wind environment. Although these factors are often relatively overlooked in studies of high-density neighborhoods, their mechanisms of action should not be underestimated. As vital green infrastructure, urban trees exert a dual effect on wind fields. On one hand, tree canopies create a drag effect on airflow by increasing surface roughness, and the structure of tree branches and leaves dissipates wind kinetic energy, thereby reducing near-surface wind speeds^[14]. Studies indicate that dense rows of street trees can reduce average wind speeds in street canyons by 20%–40%, with this dampening effect being particularly pronounced under high-wind conditions^[15]. Linear or continuous tree belts can form “windbreaks” effectively attenuating incoming wind speeds and protecting downwind areas from strong winds^[16]. On the other hand, the spatial layout and morphological characteristics of trees also influence the fine-scale structure of the wind field: parameters such as canopy height, density, and wind permeability determine the ease with which airflow penetrates the canopy, thereby affecting the wind speed distribution on the leeward side of the trees^[17]. It is worth noting that improper vegetation configuration may also have negative effects: overly dense trees may obstruct natural ventilation in street canyons, leading to localized air stagnation; conversely, isolated tall trees may induce accelerated flow around them, actually increasing wind speeds at specific locations.

The impact of topographic variations on the urban wind environment is equally significant, particularly in mountainous cities or coastal areas with complex terrain. Topography exerts a macro-regulatory influence on the urban wind field by altering the structure of the atmospheric boundary layer as well as the direction and speed of the incoming wind. When wind passes over terrain such as ridges and slopes, it creates an acceleration effect on the windward slope and a vortex shedding zone on the leeward slope; these terrain-induced wind speed variations can exceed 50%^[18]. In coastal cities, the orientation of the coastline and the undulations of the nearshore topography directly influence the intensity

and penetration depth of the sea-land breeze circulation, thereby shaping the baseline wind environment of coastal districts^[19]. Furthermore, microtopography within the city—such as artificial mounds, sunken plazas, and elevated platforms—can alter wind flow paths at the local scale. Studies have found that thoughtful topographic design can redirect strong winds away from sensitive areas or use gentle slopes to reduce wind speed gradients, thereby improving wind comfort at pedestrian height^[20].

In high-density urban environments, the combined effects of building form, vegetation distribution, and topographic conditions create a complex, multi-scale wind environment system. Buildings dominate the wind field structure at the block scale, vegetation provides local microclimate regulation, and topography establishes the macro-scale pattern of the regional wind environment^[21]. Understanding the synergistic effects of these three factors is crucial for comprehensively evaluating and optimizing urban pedestrian level wind environment. However, existing research has largely focused on the single dimension of building form, with relatively insufficient quantitative studies on vegetation and topographic elements, leaving room for future in-depth exploration.

1.2 Research Objectives and Significance

1.2.1 Research Objectives

This study aims to establish a rapid assessment and optimization design methodology based on urban morphological parameters to address pedestrian level wind environment issues in high-density coastal neighborhoods during strong wind conditions. The specific research objectives include the following three aspects:

First, to construct a block-scale urban morphological parameter system. By systematically identifying key morphological elements influencing the block's wind environment, this study extracts quantifiable morphological parameters, including spatial characteristics such as building height, density, massing combinations, street width-to-height ratios, and building alignment patterns. These parameters must possess clear physical significance and be easily obtainable and calculable, thereby providing operational input variables for subsequent pedestrian level wind environment assessments^[22]. Second, establish

a correlation model between morphological parameters and pedestrian level wind environment indicators. Using CFD numerical simulation technology, systematically simulate the wind fields within blocks under different combinations of morphological parameters to obtain key pedestrian level wind environment assessment indicators, such as wind speed ratios at pedestrian height and wind acceleration ratios. Based on this, employ statistical analysis and machine learning methods to identify quantitative relationships between morphological parameters and pedestrian level wind environment indicators, thereby constructing an assessment model capable of rapidly predicting high-risk locations for pedestrian level wind environment within blocks. This model will significantly reduce the time and computational costs associated with traditional CFD simulations, providing an efficient tool for pedestrian level wind environment assessment in the early stages of urban design^[23]. Finally, targeted urban design optimization strategies are proposed. Based on the high-risk pedestrian level wind environment zones and key morphological parameters identified by the assessment model, morphological control strategies—including adjustments to building layout, optimization of street space, podium design, and vegetation planning—are proposed from an urban design perspective. These strategies aim to improve the wind environment within blocks at the source, reduce the risk of localized strong winds, and enhance pedestrian level wind environment and comfort at pedestrian levels, thereby providing scientific evidence and practical guidance for the sustainable development and resilience enhancement of high-density coastal cities^[10].

Through research across these three dimensions, this paper seeks to deepen theoretical understanding of the relationship between urban form and pedestrian level wind environment, establish rapid assessment tools methodologically, and provide practical, actionable optimization pathways for urban design, ultimately serving to enhance pedestrian level wind environment and improve the quality of the human living environment in high-density coastal cities.

1.2.2 Research Significance

The urban wind environment is one of the key physical environmental factors influencing urban livability and safety. With the acceleration of global urbanization, high-rise,

high-density development models—while conserving land—have also significantly altered the near-surface wind field structure, giving rise to complex “wind environment issues.” Among these, the phenomenon of drastic wind speed amplification in localized areas due to inappropriate urban form has become a widespread challenge facing high-density urban centers and redevelopment zones. Localized strong winds at pedestrian height not only pose serious safety risks—such as causing pedestrians to fall, being struck by flying debris, or even endangering lives during extreme weather—Furthermore, they severely undermine the comfort and vitality of public spaces, reducing people's willingness to engage in outdoor activities, increasing the prevalence of underutilized spaces, and ultimately eroding the quality of urban public life. Therefore, conducting scientific assessments of pedestrian level wind environment and providing effective strategies to address it are intrinsic requirements for enhancing urban resilience and creating a healthy, livable environment, and they carry significant practical urgency.

1.3 Conceptual Definition

1.3.1 Block Scale

The block scale is an intermediate spatial level in urban research, situated between individual buildings and the city as a whole. It typically refers to a spatial unit enclosed by several adjacent streets and possessing a certain degree of functional integrity. In terms of spatial scope, the block scale generally covers an area ranging from several hundred meters to one kilometer on each side, encompassing multiple buildings as well as the streets, squares, and other public spaces between them^[24]. This scale holds particular significance in urban wind environment research: it reflects both the disturbance effects of individual buildings on local wind fields and the overall wind environment characteristics formed by groups of buildings^[22]. In recent years, as urban renewal practices have deepened, the block scale has gradually become the primary focus of urban design interventions. Compared to macro-level urban master planning, research at the block scale is closer to residents' daily living spaces, and the quality of its wind environment directly affects pedestrian comfort and the vitality of public spaces. At the same time, the block scale is an appropriate scope for conducting

numerical simulations of the wind environment: this scale ensures that the computational domain contains sufficient spatial information to accurately capture the development and evolution of airflow, while keeping computational costs within an acceptable range^[23]. Therefore, this study selects the block scale as the basic spatial unit of analysis, aiming to establish a direct correlation between morphological parameters and pedestrian level wind environment assessment, thereby providing an operational decision-support tool for urban design practice.

1.3.2 Coastal high-density blocks

Coastal high-density districts refer to a specific type of urban area located in coastal zones where both building density and floor area ratio are significantly higher than in typical urban areas. Such districts typically exhibit the following core characteristics: First, geographically, they are situated adjacent to the coastline or in the core areas of coastal cities, and are subject to the direct influence of strong wind systems—such as sea breezes, monsoons, and typhoons throughout the year. Second, in terms of building form, they exhibit a high-rise, high-density spatial structure, with building coverage typically exceeding 30%, a floor area ratio of 5.0 or higher, and building heights generally exceeding 100 meters, forming an urban fabric characterized by a "forest of high-rise buildings"^[25]. Third, in terms of functional attributes, these areas are predominantly commercial, business, or high-density mixed-use residential zones. With dense pedestrian traffic and vibrant public spaces, they place extremely high demands on the comfort and safety of the pedestrian wind environment^[26]. Finally, regarding wind environment characteristics, due to the blocking, acceleration, and disturbance effects of dense clusters of high-rise buildings on incoming winds, complex and variable local wind fields often form within coastal high-density neighborhoods. Localized areas are prone to the "wind tunnel effect," where wind speeds increase sharply, or to strong vortices on the leeward sides of buildings. Under extreme weather conditions such as typhoons, this is even more likely to trigger serious pedestrian level wind environment issues^[27].

Typical examples of coastal high-density neighborhoods include:

1. Mong Kok and Central districts in Hong Kong: As one of the areas with the highest

building density in the world, Hong Kong's central districts are characterized by a dense cluster of high-rise buildings, narrow streets, and extremely high building coverage, making them a classic case study for the wind environment in coastal high-density neighborhoods .

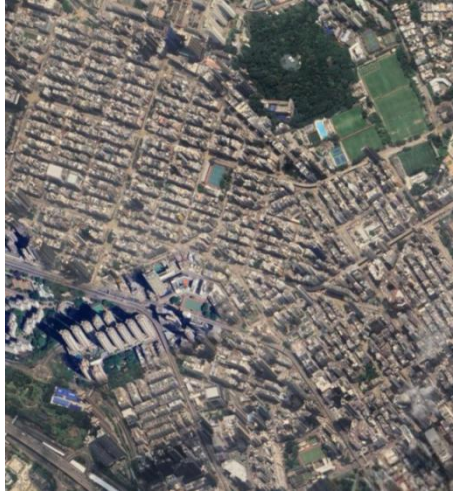


Figure 1-1 Urban morphology of the Mong Kok district in Hong Kong

(Image source:: <https://earth.google.com/>)

2. Shenzhen Futian Central Business District: As a frontier city of China's reform and opening-up, Shenzhen's Futian CBD is home to a large concentration of super-high-rise buildings, with extremely high floor area ratios and building densities. Adjacent to the Pearl River Estuary, it is subject to monsoons and typhoons year-round .



Figure 1-2 Urban Form of Futian District, Shenzhen (Image source: <https://earth.google.com/>)

3. Shanghai Lujiazui Financial District: Located on the banks of the Huangpu River, the

Lujiazui area serves as Shanghai's financial hub. The district features a dense concentration of super-tall buildings, forming a typical high-density coastal urban form, with prominent wind environment issues^[29].



Figure 1-3 Urban Form of the Lujiazui Area in Shanghai

(Image source: <https://earth.google.com/>)

4. Singapore's Marina Bay Area: As a tropical island city-state, Singapore's Marina Bay CBD features a high concentration of high-rise buildings and is situated within the Southeast Asian monsoon belt, making it a key reference for studying wind environments in high-density coastal districts under tropical climates^[30].

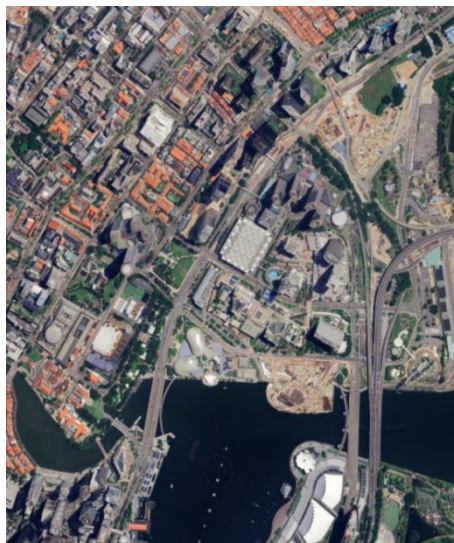


Figure 1-4 Urban Form of Singapore's Marina Bay Area

(Image source: <https://earth.google.com/>)

5. Guangzhou's Zhujiang New Town: As a major financial and business hub in South China, Zhujiang New Town features a large number of super-high-rise buildings. Adjacent to the Pearl River and significantly influenced by monsoons and typhoons, it is a typical example of a high-density coastal neighborhood .



Figure 1-5 Urban Form of the Guangzhou Zhujiang New Town Area

(Image source: <https://earth.google.com/>)

1.3.3 Urban Morphological Parameters

Urban morphological parameters constitute a system of indicators that quantitatively describe the spatial characteristics of a city. They present the compositional features of urban space in a numerical format, thereby accurately conveying urban morphological information. From the perspective of the hierarchical structure of urban spatial texture elements, urban morphological parameters can be divided into three core levels: the street network level, the block perimeter level, and the building cluster level. Based on this hierarchical framework, urban morphological parameters can be further subdivided into two major categories: basic element parameters and spatial combination parameters. Typical parameters include road network density, average building height, and floor area ratio (FAR). These parameters can be quantitatively extracted and calculated within a Geographic Information System (GIS) platform using vectorized spatial texture data models^[32]. During the calculation process, a rasterization method is typically employed to spatially discretize the urban texture into grid cells of a specific scale, and the results of parameter calculations are visualized using raster

maps^[33]. The size of grid cells must be flexibly adjusted according to the spatial scale of the study: in ventilation potential analysis at the urban level, grid cells are typically set to tens to hundreds of meters; whereas in wind environment studies at the micro-scale of city blocks, smaller grid cells are required to achieve higher spatial resolution.

In the field of wind environment research, urban morphological parameters serve as a bridge connecting the city's physical space with the dynamic characteristics of the wind field. The mechanisms by which different types of morphological parameters influence the wind environment vary significantly: parameters such as building density and building height primarily affect the vertical distribution and attenuation characteristics of wind speed by altering the urban surface roughness; whereas parameters such as street orientation and street aspect ratio govern the airflow organization patterns and ventilation efficiency within street canyons; while parameters such as the spatial layout of building clusters and building spacing determine the occurrence and intensity of local wind speed amplification effects or vortex phenomena^[9]. Therefore, the scientific selection of urban morphological parameters closely related to the wind environment, and the establishment of quantitative response relationships between these parameters and wind environment evaluation indicators, constitute the theoretical foundation and technical prerequisite for optimizing the urban wind environment through morphological regulation.

1.3.4 Pedestrian-Level Wind Environment Assessment

The evaluation of the PLW environment primarily focuses on wind speed variations at pedestrian height (typically defined as 1.5 to 2 meters above ground level). When wind speeds at this height exceed specific operational thresholds, it may induce strong aerodynamic effects on pedestrians, leading to difficulties in walking or a loss of physical balance^[34]. Internationally recognized PLW environment standards indicate that when average wind speeds exceed 15 m/s or gust speeds exceed 20 m/s, the wind environment deteriorates to an extreme state, and outdoor activities should be avoided^[35]. Furthermore, the wind comfort and environment assessment guidelines established by the Dutch Standard (NEN 8100) classify the pedestrian wind environment into multiple quality levels, explicitly defining the extreme condition (often referred to as the "danger" threshold in standard terminology) as

areas where gust speeds exceed 15 m/s for more than 0.05% of the time annually^[36].

In high-density urban environments, the complex spatial arrangement of building clusters can give rise to localized wind field intensification phenomena such as the canyon effect, corner effect, and downwash. This causes wind speeds at pedestrian height in certain areas to be significantly higher than in surrounding areas, thereby creating adverse PLW conditions^[9]. These critical zones with excessive wind speeds often occur at the bases of high-rise buildings, building corners, narrow street canyons, and the junctions between open plazas and buildings^[37]. Therefore, the core objective of this study is to identify and quantify these critical zones, establish correlations between urban morphological parameters and the PLW environment, and provide scientific optimization strategies for urban design. This aims to mitigate the negative impacts of excessive wind speeds and maintain an acceptable pedestrian wind environment during daily activities and under extreme weather conditions.

1.4 Research Review

1.4.1 History and Development of Related Research

With the acceleration of global urbanization and the increasing prominence of climate change, the urban wind environment and the resulting strong wind hazards have become a focal point of concern across the fields of urban planning, architectural design, disaster management, and public safety. High-density, high-rise urban forms alter the near-surface wind field structure, potentially generating strong winds in localized areas that pose serious threats to pedestrian comfort, building safety, and even urban infrastructure. Meanwhile, the increasing frequency and intensity of extreme weather events such as typhoons and thunderstorms have further exacerbated the risk of urban strong wind disasters^[38].

The history of urban wind environment research is closely intertwined with the development of urban construction, computational technology, and disaster science. Its evolution can be broadly divided into three phases. The first phase is that of early exploration and the emergence of research questions (1950s – 1970s). This period marked the nascent stage of wind engineering. The origins of this research can be traced back to the 1950s, when researchers began studying wind effects through laboratory simulations and early numerical

models^[39]. However, specific attention to the urban wind environment did not begin until the 1970s. With the proliferation of high-rise buildings worldwide, issues related to the wind environment around buildings began to emerge. Research by the AIJ in Japan indicates that “building wind hazards” emerged as a distinct issue in the 1970s alongside the construction of high-rise buildings^[1]. These wind hazards not only affect pedestrian comfort but have even led to legal disputes regarding the impacts of the wind environment. Research methods during this phase primarily relied on wind tunnel experiments and field observations, focusing on understanding the mechanisms by which high-rise buildings influence local wind fields. Starting in the 1980s, advances in computational technology brought revolutionary changes to wind environment research. The introduction of turbulence models made it possible to simulate complex urban wind fields using numerical methods^[40]. During this period, researchers began to systematically develop and apply CFD technology. Concurrently, modeling research targeting specific severe wind events (such as hurricanes) also made progress; for instance, predictive models for hurricane wind fields and wind speeds emerged as early as the 1990s. This phase marked a shift in the research paradigm from a focus on physical experiments to a combined approach of physical experiments and numerical simulation, significantly expanding the depth and breadth of research^[41]. Entering the 21st century, with the rapid increase in computing power, CFD technology has become the mainstream tool for urban wind environment research. Over the past two decades, the volume of relevant research literature has grown exponentially. The scale of research has continuously deepened from the macro level of urban climate to the micro levels of city blocks, building clusters, and pedestrians^[42,43]. This is attributed to the widespread adoption of high-fidelity simulation methods; CFD methods, represented by Reynolds-averaged simulation (RANS) and large-eddy simulation (LES), have been extensively applied to assess wind speed, wind pressure, and turbulence characteristics around urban canyons and building clusters^[38,42]. In particular, the LES method, due to its ability to more accurately capture the instantaneous and unsteady characteristics of wind, is increasingly used for detailed analysis of urban wind disasters, such as simulating complex flow fields within cities during typhoons^[44].

1.4.2 Methods for Urban Pedestrian level wind environment Assessment

After decades of development, research on urban wind environments and severe wind hazards has evolved into a comprehensive research system encompassing theory, simulation, and observation. Its core research methods primarily consist of the following three complementary approaches: wind tunnel experiments, numerical simulation, and field observations and data analysis. Among these, wind tunnel experiments serve as the most traditional and direct research method. By physically simulating urban layouts and building forms using scaled models, wind tunnel experiments can provide high-precision wind pressure and wind speed data, serving as a crucial benchmark for verifying the accuracy of numerical models^[45]. However, they are costly, time-consuming, and struggle to fully simulate the complex turbulent characteristics of the real atmospheric boundary layer^[46].

Numerical simulation, centered on CFD, is currently the most widely used research method. Its advantages include high flexibility, relatively low cost, and the ability to provide detailed flow field information across the entire spatial domain^[46]. Steady-state Reynolds-averaged simulation (SRANS): Due to its high computational efficiency, it remains the dominant method in engineering applications such as assessing pedestrian-level wind comfort^[43]. Large-Scale Turbulence Simulation (LES) and Hybrid Models: LES can more accurately resolve large-scale turbulent vortex structures, making it crucial for studying urban wind environments, gusts, and even wind-related disasters under extreme weather conditions; it is currently a cutting-edge focus in academic research^[44].

Field Observation and Data Analysis: Field observation is the fundamental means of obtaining real-world data. In addition to traditional weather stations, new observation technologies such as phased-array weather radars, lidar (*LiDAR*), and dense ground-based meteorological observation networks are used to capture the fine-scale structures of strong wind events^[47]. Furthermore, researchers are increasingly utilizing long-term historical meteorological reanalysis data (such as ERA5 and 20CRv3) to assess trends in historical storms and regional wind hazard risks^[48].

In research on urban wind environments, domestic studies have a very distinct problem-solving orientation, and most of the final conclusions and results directly serve urban

planning and design practices. Specifically, these studies emphasize both assessment and optimization; research generally follows a technical approach of “simulation and evaluation—identifying problems—proposing strategies”^[49,50]. Furthermore, the final outcomes are often concrete and actionable urban design improvement strategies, landscape adaptation strategies, or planning guidelines, aiming to directly translate research findings into technical tools for planning management and decision-making references for designers^[51–53]. However, there is relatively little research on urban morphological parameters: Lin Tao et al. conducted a systematic review of research progress on rapid prediction methods for the wind environment at the urban block scale. They summarized two major technical approaches—numerical simulation and data-driven modeling—analyzed the prediction accuracy, efficiency, and applicable scenarios of various methods, and pointed out that while numerical simulation is reliable, it entails high computational costs, whereas data-driven models hold the potential for efficient, real-time prediction and represent a primary future research direction. They also provided a methodological framework and application references for adaptive design of the urban wind environment^[54]. In contrast, research on pedestrian level wind environment and severe wind hazards has primarily focused on structural safety in civil engineering or natural disasters at the meteorological scale^[55–57]; studies examining the impact of specific urban block morphologies on the wind environment in urban design remain relatively scarce.

In contrast, research on urban wind environments in English-language journals is more extensive and tends to focus on foundational, ground-level studies. A significant portion of this research centers on the relationship between urban morphological parameters and the prediction, simulation, and assessment of severe wind hazards, and is frequently published in leading urban climate journals such as *Building and Environment* and *Urban Climate*. For example, Yang D et al. conducted high-resolution numerical simulations of the Lujiazui area in Shanghai under typhoon conditions by coupling the WRF mesoscale model with the PALM large-eddy simulation model, analyzing the relationship between various urban morphological parameters and pedestrian wind environment indicators. The study found that building floor

area density (λ_p) exhibited the strongest and most stable correlation with pedestrian risk indicators. Based on this, a probability distribution function based on λ_p was developed to assess extreme wind risk at specific probability levels, providing an effective and practical single-parameter quantitative method for evaluating pedestrian level wind environment in typhoon-prone cities^[58]. Furthermore, Takemi et al. used Large Eddy Simulation (LES) to investigate the relationship between wind field characteristics and strong wind disaster risks under the actual complex urban morphology of Kyoto, Japan. The study found that building height variability and layout complexity significantly increased the turbulence and gust intensity within the urban canopy: average wind speeds were higher on downwind main roads and in open areas, while instantaneous strong winds and high gust factors were more likely to occur in areas with a mix of high-rise and low-rise buildings. The study indicates that the lower the building plan density index (λ_p), the more pronounced the gust effects, and that actual urban building layouts are more likely to induce extreme wind conditions than idealized uniform layouts, suggesting that refined LES models can effectively assess urban strong wind disaster risks^[44].

On the other hand, as early as 2011, Edward NG et al. applied regression analysis based on wind tunnel tests to investigate the relationship between the frontal area index—a key urban morphological parameter and important indicator for urban ventilation assessment—and the wind speed ratio. They further proposed the possibility of using this single urban morphological parameter to rapidly predict the wind speed ratio. Xu Y et al. employed an efficient calculation method based on remote sensing data for building height, urban coverage, sky visibility factor, and frontal area index, and used this to establish a regression-based predictive model for urban thermal and wind environments^[59]. He Y et al. utilized wind tunnel experiments and GIS analysis to investigate the impact of morphological parameters of open spaces on pedestrian wind environments in high-density cities. They found that urban irregularity is negatively correlated with the wind environment and proposed a new parameter, “open space width,” that incorporates irregularity to accurately and rapidly predict urban wind environment performance, thereby providing a quantitative design basis for optimizing the

wind environment in high-density cities^[47]. As such, the use of urban morphological parameters for rapid prediction in urban wind environment research has been widely adopted. Furthermore, a large body of research has confirmed that urban morphological parameters such as average building height, building height variation, and the frontal area index (FAI) can accurately quantify the effects of wind attenuation, vertical exchange, and total airflow resistance in urban environments^[50,60,61]

1.4.3 Shortcomings and Limitations of Existing Research

First, real-world urban wind fields result from the combined effects of mesoscale meteorological backgrounds (such as typhoons and monsoons) and microscale urban morphology. A core bottleneck in current urban wind environment research lies in the difficulty of bridging the gap between “mesoscale meteorological backgrounds” and “microscale complex urban blocks.” On the one hand, real-world wind fields are driven by macroscale weather systems (such as typhoons and monsoons), but under the existing meteorological perspective, the resolution of mesoscale meteorological models typically stops at the kilometer scale, unable to resolve the fine-scale structures within cities and thus providing only coarse boundary conditions; On the other hand, while micro-scale simulations (such as LES/PALM) can resolve buildings, traditional aerodynamic parameterization schemes often fail when dealing with the extreme topography of high-density urban areas (such as Mong Kok), as they cannot adequately describe the characteristics of “deep street canyons” with varying building heights. This “discontinuity” creates a research dilemma: models either become overly idealized due to the lack of real meteorological driving forces, or fail to accurately reproduce near-surface flow structures because the parameterization schemes are ill-suited, making it extremely challenging to accurately extrapolate wind conditions from the macroscopic background wind to the pedestrian level. Furthermore, the absence of urban morphology in traditional urban wind field studies has also prevented previous simulations from accurately

1.5 Research Content and Methods

1.5.1 Research Content

This study focuses on pedestrian level wind environment issues in high-density coastal

districts. Using the Mong Kok district in Hong Kong as a typical case study, it systematically conducts quantitative research on the relationship between urban form parameters and pedestrian level wind environment. The study aims to construct a rapid assessment model based on urban form parameters to provide scientific basis and practical guidance for pedestrian level wind environment optimization design in high-density cities. Specific research content includes the following aspects:

(1) Establishing a System of Urban Morphological Parameters and a Database for Pedestrian level wind environment Assessment

By systematically reviewing high-quality literature on the correlation between urban wind environments and urban form, we identified urban form parameters suitable for pedestrian level wind environment assessment in coastal high-density neighborhoods. Based on a high-precision 3D urban model and GIS platform of the Mong Kok district in Hong Kong, we established a multidimensional quantitative indicator system covering building form, open spaces, and other key spatial elements. We developed a Python-based batch calculation algorithm to efficiently extract and spatially represent urban morphological parameters, thereby creating a comprehensive database of urban morphological parameters. Through sensitivity analysis, we determined the optimal computational scale, providing high-quality morphological data support for subsequent wind field simulations and model construction.

(2) High-Precision Numerical Simulation of Urban Wind Fields Using PALM-4U

Employing the Large Eddy Simulation (LES) method, conduct high-precision 3D wind field numerical simulations of the Mong Kok district in Hong Kong using the PALM-4U modeling platform. Boundary conditions were set using real meteorological data, taking into account wind field characteristics under different wind direction scenarios. The simulation yielded detailed wind speed distribution data at pedestrian height levels, with a focus on analyzing the spatial distribution patterns of key pedestrian level wind environment indicators such as average wind speed, gust intensity, and wind speed amplification effects. Potential high-risk locations for pedestrian level wind environment within the block were identified,

and the mechanisms by which complex urban morphology influences near-surface wind fields were revealed, providing reliable flow field data samples for the establishment of pedestrian level wind environment assessment and prediction models.

(3) Development of a Rapid Pedestrian level wind environment Prediction Model Based on Urban Morphology Parameters

By comprehensively applying analytical methods such as linear regression and machine learning, this study systematically investigates the correlation between urban morphological parameters and pedestrian level wind environment assessment indicators. Through correlation analysis, key morphological parameters with significant influence on pedestrian level wind environment are identified, core variables are selected, and a statistically significant rapid prediction model is constructed. The model is validated using the Mong Kok district in Hong Kong to assess its predictive accuracy, scope of application, and generalization capability. Spatial visualization of the model's prediction results is performed using a GIS platform to enable rapid identification of high-risk pedestrian level wind environment areas, thereby providing a scientific and efficient evaluation tool for urban design decision-making.

(4) Proposing Urban Design Optimization Strategies and Guidelines for Pedestrian level wind environment

Based on the evaluation results of the predictive model and the sensitivity analysis of urban morphological parameters, this study systematically proposes pedestrian level wind environment optimization design guidelines for high-density coastal neighborhoods across multiple dimensions, including building layout, open space configuration, and building height control. Operational morphological regulation strategies are formulated, clarifying the optimization objectives and control thresholds for key parameters. A pilot renovation design project is conducted in a typical high-risk area of the Mong Kok district. By selectively optimizing urban morphological parameters and utilizing the PALM-4U simulation tool and predictive models to validate the optimization results, the practical application value of the design strategies is demonstrated, providing a replicable practical model for pedestrian level wind environment planning and design in similar cities.

1.5.2 Research Methods

This study employs corresponding research methods tailored to different research components:

(1) Introduction (Chapter 1): Literature Review

Through a systematic review of literature on urban wind environments, this study focuses on high-level research findings regarding the relationship between urban morphological parameters and wind environments. It summarizes the urban morphological parameter systems adopted in existing studies and their potential applications in pedestrian level wind environment assessment. Additionally, it reviews wind environment evaluation indicators used in research on urban strong wind disasters, assesses their applicability within this study's pedestrian level wind environment evaluation framework, and provides a theoretical basis for subsequent parameter selection and model construction.

(2) Construction and Analysis of the Urban Morphological Parameter Database (Chapter 2): Empirical Synthesis, Computational Analysis, and Data Visualization

Based on literature reviews and the spatial morphological characteristics of high-density coastal neighborhoods, a system of urban morphological parameters suitable for this study is systematically defined. Taking the Mong Kok neighborhood in Hong Kong as the study subject, a high-precision 3D urban model is established using a GIS platform. Using the Python programming language, a batch calculation algorithm was developed to efficiently extract urban morphological parameters. By setting grid cells at different scales and conducting sensitivity analyses, the optimal spatial resolution for parameter calculation was determined. Finally, the spatial visualization and distribution analysis of morphological parameters were completed on the GIS platform.

(3) PALM-4U Simulation Setup, Process, and Results Analysis (Chapters 3 and 4): Computational Fluid Dynamics Simulation Method

An advanced Large Eddy Simulation (LES) numerical method was adopted to conduct high-precision urban wind field simulations based on the PALM-4U model platform. Simulation parameters were configured in accordance with relevant technical specifications, including building geometric modeling, real-world meteorological boundary conditions,

meshing strategies, and solver parameter settings. The simulation yielded wind field distribution data at pedestrian height for the Mong Kok district under various wind direction conditions. This allowed for the analysis of spatial variations in wind speed and the gust amplification effect, the identification of potential high-risk locations for pedestrian level wind environment, and the provision of high-quality sample data for subsequent modeling.

(4) Development of a Pedestrian level wind environment Prediction Model Based on Urban Morphological Parameters (Chapter 5): Regression Analysis, Data Visualization, and Machine Learning

Simple linear regression analysis was employed to investigate the correlation between individual urban morphological parameters and pedestrian level wind environment indicators, identifying key parameters with significant influence on pedestrian level wind environment. Building on this, multiple linear stepwise regression analysis was used to screen key variables and construct a rapid pedestrian level wind environment prediction model based on urban morphological parameters. The model was validated in the Mong Kok area of Hong Kong to assess its predictive accuracy and applicability. The analysis results are visualized using a GIS platform to intuitively demonstrate the mechanisms of parameter influence and the model's predictive performance.

(5) Guidelines for Optimizing Urban Form for Pedestrian level wind environment and Exemplary Renovation Designs (Chapter 6): Applied Research Method, Urban Design Method

Based on the evaluation results of the predictive model and the sensitivity analysis of urban morphological parameters, urban design optimization guidelines aimed at enhancing pedestrian level wind environment are proposed. Actionable morphological control strategies are formulated across multiple dimensions, including building layout, open space, and building height. A typical high-risk area in the Mong Kok district was selected for an exemplary renovation design. Through targeted optimization of morphological parameters and validation via PALM-4U simulation, the practical effectiveness of the optimization strategies is demonstrated, providing scientific guidance for pedestrian level wind environment planning

and design in high-density coastal districts.

1.6 Research Framework

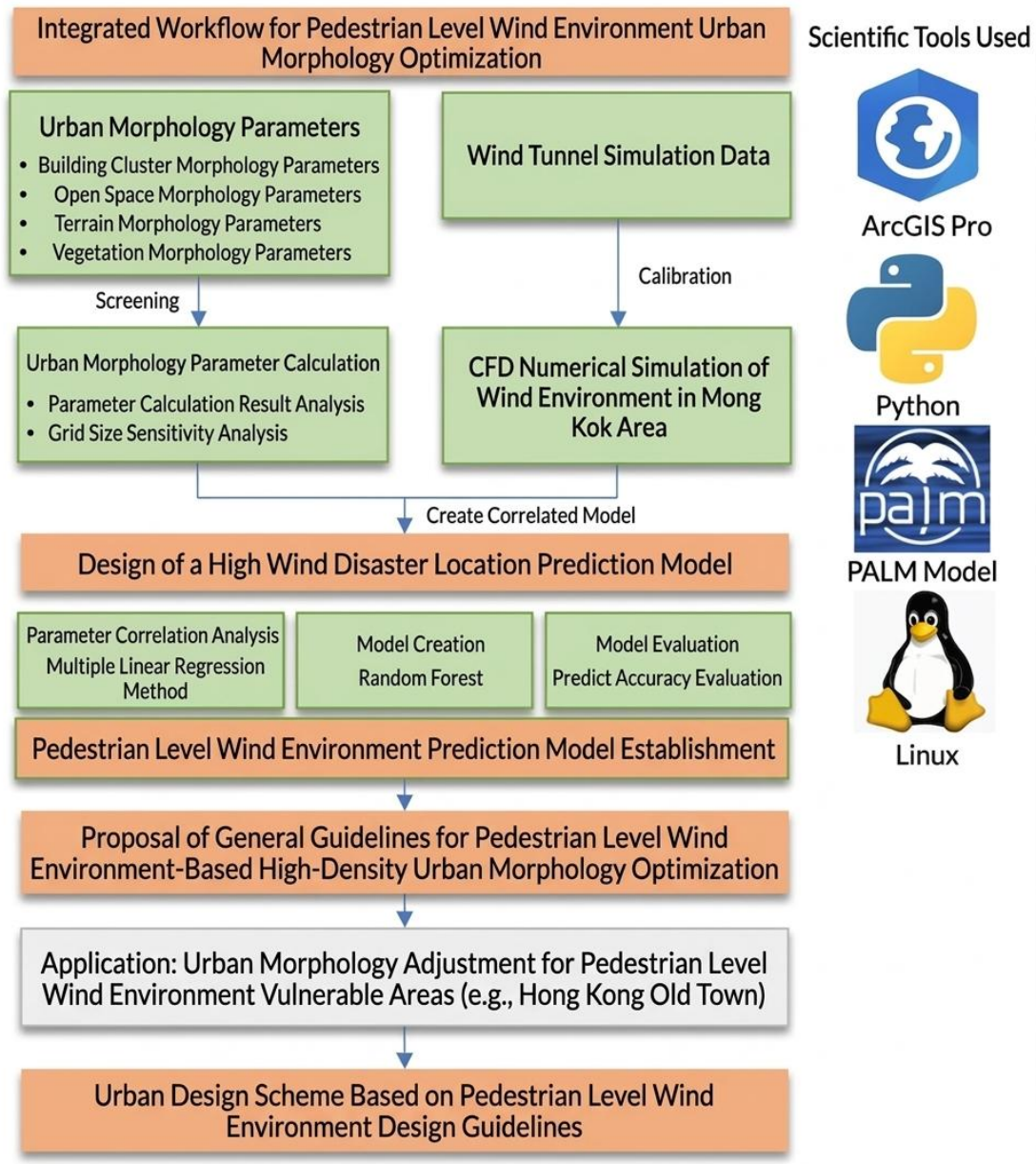


Figure 1-6: Workflow Framework (Figure by author.)

Chapter 2 Construction and Research of the Urban Morphological Parameter Database

Urban morphological parameters, as core indicators for quantifying urban spatial characteristics, play a crucial role in urban planning and design practices. These parameters not only systematically describe the geometric features and organizational patterns of urban spaces but also provide scientific tools for in-depth exploration of the complex relationships between urban form and microclimate environments. By establishing a correlation model between urban morphological parameters and wind environment characteristics, researchers can quantitatively assess the impact of different spatial configurations on urban ventilation performance, thereby providing data support for optimizing the urban wind environment.

Based on the need for wind environment assessment at the block scale and considering the spatial morphological characteristics of high-density coastal cities, this chapter establishes an urban morphological parameter system applicable to the Mong Kok district of Hong Kong. Using a GIS platform and a 3D urban model, this study systematically established a database of urban morphological parameters for the Mong Kok area of Hong Kong, covering multidimensional quantitative indicators of building morphology, open spaces, and other key spatial elements. Building on this foundation, a typical Mong Kok block was selected as a case study to systematically extract and analyze the quantitative characteristics of its urban spatial morphology, revealing the morphological distribution patterns of high-density blocks and laying a solid data foundation for the subsequent development of pedestrian level wind environment assessment models.

2.1 Definition of Urban Morphological Parameters

This study employed a literature review approach to systematically identify scientifically sound and empirically validated urban morphological parameters from high-level academic literature on the correlation between urban wind environments and urban morphology. During the parameter selection process, particular attention was paid to research findings on high-density urban blocks in coastal areas to ensure that the selected parameters

accurately reflect the spatial morphological characteristics of the study's subject.

The urban morphological analysis and calculations in this study were primarily conducted using a GIS platform. The Hong Kong region possesses a well-established GIS research infrastructure and high-precision spatial datasets; its 2.5D building data files and topographic elevation data both exhibit high geometric accuracy, significantly reducing the workload of data preprocessing. Building upon the researcher's prior work on urban morphological parameter calculations, this study established calculation units for morphological parameters using a grid-cell division method. Each calculation unit contains several building entities, and a single urban morphological parameter value reflects the overall spatial morphological characteristics within that unit. Based on this research design, this study excludes micro-level parameters such as building enclosure ratio and street aspect ratio, which describe the spatial relationships between individual buildings and roads. Furthermore, in high-density built environments, urban ventilation performance primarily depends on the morphological configuration of all open spaces near the ground surface and the influence of topographic undulations on the wind field. Coastal cities often feature complex topographic conditions; changes in slope gradient, aspect, and elevation can significantly alter local wind speed distributions and wind direction characteristics, thereby affecting wind environment safety at the block scale. Therefore, when constructing the morphological parameter system, this study not only replaces traditional street morphological parameters with open space morphological parameters but also incorporates topographic factors as key influencing variables to more comprehensively characterize the spatial elements affecting the block-scale wind environment.

Table 2-1 Summary of Urban Morphological Parameters and References

	形态参数名称 Morphological parameters	缩写 Abbre viation	定义 Definition	参考文献 Reference
建筑形态 参数 Building Blocks	开放空间覆盖率 Open space coverage ratio	C	Percentage of total open space area to total parcel area	[62-64]
	平均建筑高度 Mean building height	Hm	Mean of all building heights	[64-68]
	建筑高度离散率 Building height deviation	Hv	Difference between the height of the building and mean building height	[44,69-72]
	容积率 Floor area ratio	FAR	Ratio of total above-ground building area to total plot area	[44,73-76]
	天空可视因子 Sky view factor	SVF	Ratio of the visible hemisphere of the sky to the hemisphere of the unobstructed sky as viewed from ground level	[77]
	建筑表面面积比 Building Surface to Plan Area Ratio	λ_b	Ratio of both the horizontal and vertical surface of the building to total plot area	[78]
	裙房形态参数 Podium Aspect Ratio	B/H	The aspect ratio of the podium is calculated as its width (B) divided by its height (H).	[79,80]
开放空间 形态参数 Open Spaces	建筑屋顶坡度 Slop of roof	/	The tilted angle of the roof	[81]
	中心线密度 Centerline density	D	Ratio of total open space centerline length to parcel area	[82]
	开放空间宽度 Open space width	W	Ratio of total open space area to total length of open space centerline	[83]
	开放空间交角旋 转角度 Open space intersection	R	Difference between actual angle and orthogonal angle (90°) at open space intersections	[84]

	rotation angle		
	开放空间道路曲折度	S	Ratio between the actual length of the open space centerline and the length of the roadway intersection alignment [85]
	Open space road sinuosity		
	平均街道高宽比	AAR	The ratio of the average height (H) of the street to its average width (D), denoted as (H/D). [86]
	Average Aspect Ratio		
地形形态参数	迎风坡坡度	/	ratio of the vertical height between the crest and foot of the slope (z) and length between crest and foot measured in the direction of the wind [86,87]
Terrain	Upwind Slope		(L)

2.1.1 Building Morphological Parameters

In response to the spatial characteristics of building clusters, this study has developed a comprehensive system of morphological description indicators, specifically comprising the following seven core parameters: Open Space Coverage Ratio, Average Building Height, Coefficient of Variation of Building Height, Plot Floor Area Ratio, Skyline Visibility Coefficient, Building Facade Area Density, and Ground-Floor Podium Morphology Index.

The Open Space Coverage Ratio (C) quantifies the proportion of non-building land area within the site relative to the total land area. This indicator reflects both the density of the site and, to a certain extent, the level of land use intensification; its value is calculated using Formula (2-1). The building density indicator is complementary to the Open Space Coverage Ratio; since their sum is always 1, building density is not calculated separately.

$$C = \frac{\sum_{i=1}^n A_i}{A_T} \quad (2-1)$$

In the formula, A_i represents the area of the i open space, and A_T represents the total area of the site. To focus on the mechanisms by which building form and spatial organization influence ventilation performance, this study excludes ancillary facilities such as railings and fences when defining open space, classifying all areas other than the building structure itself as open space.

The mean building height (H_m) is calculated as the weighted average of the heights of

all buildings within the site. It characterizes the overall vertical scale of the buildings and, to some extent, indicates the level of development intensity within the site. The calculation method is shown in Equation (2-2).

$$H_m = \frac{\sum_{i=1}^n (H_i * B_i)}{\sum_{i=1}^n B_i} \quad (2-2)$$

In the formula, H_i represents the height of the i building within the plot, and B_i represents the ground-floor area of that building. In typical multi-story, high-density urban blocks, building heights generally fall within the range of 9 to 24 meters.

The building height coefficient of variation (H_v) is used to characterize the degree of dispersion of the heights of individual buildings within a plot relative to the average elevation, thereby reflecting the undulating characteristics of the building skyline. It is calculated according to Formula (2-3).

$$H_v = \frac{\sum_{i=1}^n B_i * |H_i - H_m|}{\sum_{i=1}^n B_i} \quad (2-3)$$

In the formula, H_i represents the actual height of the i building; the larger the ground floor area of a building, the greater its weighting in determining the overall range of the height deviation coefficient.

The Floor Area Ratio (FAR) is defined as the ratio of the total above-ground floor area to the total site area. This indicator is used to measure the intensity of land use, and its calculation formula is shown in Equation (2-4). Urban form parameters similar in concept to this indicator include building volume density and building mass proportion. If a uniform floor-to-ceiling height assumption is applied to buildings within the site during the calculation process, the FAR can be derived from the open space coverage ratio C and the average building height H_m ,

$$FAR = (1 - C) * H_m / H_f \quad (2-4)$$

where C represents the open space coverage ratio, H_m is the average building height, and H_f is the standard floor height. To simplify the calculation process, this study uniformly sets the standard floor height H_f for buildings in the Mong Kok district to 3 meters.

The Sky View Factor (SVF), also referred to in relevant literature as the sky visibility factor, sky visibility, or sky angle coefficient, is a parameter used to quantify the ratio of the visible sky hemisphere at a ground-level observation point to the theoretical unobstructed sky hemisphere. It serves to characterize the openness of urban space. This parameter is comprehensively influenced by the height of vertical elements such as buildings and vegetation, as well as their spatial layout. Traditional SVF calculation methods typically involve capturing panoramic images using a fisheye lens and determining the value by calculating the proportion of the visible sky area relative to the total image area. In contrast, this study employs Formula (2-5) for calculation. Furthermore, the SVF calculation results are closely related to the selected study radius R , which determines the spatial scale of the buildings and sky areas included in the calculation. In the implementation of this study, the average SVF for a plot was obtained by calculating the SVF at multiple road intersection nodes and taking the arithmetic mean of these values.

$$SVF = 1 - \frac{\sum_{i=1}^n \sin \gamma_i}{n} \quad (2 - 5)$$

In the formula, γ_i represents the angle of elevation of obstacles measured in the i azimuth direction, and n represents the number of azimuth samples included in the calculation (generally no fewer than 36).

The Podium Morphology Parameter (PMP) is quantified in this paper using the Podium Frontal Area Index (FAI_{podium}). As the low-rise volume in a “podium-tower” complex, the podium is concentrated in the 15–20 m height zone at the base of the building. This height range is not only the geometric zone directly perceptible to pedestrians but also the vertical level where the wind field at the pedestrian level is most significantly affected by building obstruction, recirculation, and turbulence. The plan layout (depth and extent), continuity (whether there are breaks or misalignments), façade openings and permeability, and

orientation relative to the onshore flow of the podium determine the continuity of the windward surface and the windward projection area, thereby influencing the deceleration of the onshore flow, the point of flow separation, the location of the wake zone, and the distribution of turbulence intensity; These variations directly affect the average wind speed, wind speed gradient, and short-term gust concentrations at the pedestrian level, which in turn impact thermal comfort, wind-related risks, and pollution dispersion. The use of FAI_{podium} condenses the geometric obstruction of the podium to the incoming flow within the 15–20 m zone into a dimensionless metric that facilitates cross-scale comparisons and design alternatives—it can be used for rapid comparisons during the conceptual design phase and also serves as an optimization objective or constraint to guide adjustments to the facade and podium form.

$$FAI_{\text{podium}} = \frac{\sum_i f_i \sum_j w_{ij}(\theta_i) h_j^{\text{pod}}}{A} \quad (2-6)$$

In the formula, ' h_j^{pod} ' represents the effective height of the ' j '-th building within the 15–20 m height zone; ' $w_{ij}(\theta_i)$ ' is the windward projected width of the ' j '-th building under wind direction ' θ_i '; ' f_i ' is the wind direction weight; and ' A ' is the area of the analysis buffer zone. A larger value indicates that the podium more significantly impedes the incoming flow within the 15–20 m zone, potentially creating stronger wind speed gradients and turbulence at the top of the podium and on the leeward side, thereby having a greater impact on pedestrian comfort and safety.

2.1.2 Open Space Morphological Parameters

Relying solely on building cluster morphological parameters is insufficient to comprehensively characterize the complex and variable morphological features of open spaces in high-density coastal urban blocks. In actual coastal urban block environments, particularly in high-density areas with irregular ventilation corridor networks, the alignment of ventilation corridors and the geometric characteristics of their intersections can more accurately reveal the overall layout patterns of the block and the nature of its irregularity. This

study defines and quantifies the morphological characteristics of ventilation corridors based on the axis system of urban open spaces. The four defined categories of open space morphological parameters include: open space axis density, average open space width, open space intersection angle, and open space axis sinuosity.

Open space centerline density (D) represents the ratio of the cumulative length of open space centerlines to the block area, and is used to quantify the level of fragmentation of open space within a block. It is calculated according to Equation (2-7). The physical significance of this parameter is similar to the concept of road network density.

$$D = \frac{\sum_{i=1}^n l_i}{A_T} \quad (2-7)$$

In the formula, l_i represents the actual length of the i road segment within the block. In the context of high-density coastal blocks, a higher value of open space centerline density indicates weaker spatial continuity and more pronounced fragmentation.

The average open space width (W) represents the ratio of the cumulative area of open spaces to the cumulative length of open space axes. It is used to quantify the typical width of open spaces within a block and is calculated according to Equation (2-8). A larger average open space width implies stronger airflow penetration within the block and more efficient air exchange.

$$W = \frac{C}{D} = \frac{1 - \sum_{i=1}^n B_i}{\sum_{i=1}^n l_i} \quad (2-8)$$

In the formula, C represents the open space coverage, and D represents the open space axis density. To simplify the algorithm, the W parameter is calculated using the results of C and D.

The Open Space Intersection Rotation Angle (R) represents the deviation between the measured angle at an open space intersection node and the standard orthogonal angle (90°). It is used to quantify the degree of non-orthogonality at open space intersection nodes within a block, and is calculated according to Equation (2-9).

$$R = \frac{\sum_{i=1}^j (\alpha_i - \alpha_{regular_i})}{n} \quad (2-9)$$

In the formula, α_i denotes the actual angle between the connecting lines at an intersection node, $\alpha_{regular}$ denotes the smallest standard angle closest to α_i , and j represents the total number of intersection nodes. The larger the deviation angle value (with a maximum of 45°), the higher the degree of non-orthogonality.

Open Space Segment Sinuosity (S) represents the ratio of the measured length of an open space segment to the straight-line distance between road intersections. It is used to quantify the degree of curvature of open spaces and is calculated using Equation (2-10).

$$S = \left(\frac{\sum_{i=1}^n l_i}{\sum_{i=1}^n d_i} \right) - 1 \quad (2-10)$$

In the formula, d_i represents the Euclidean distance between the end nodes of the segment. The higher the value of the open space axis sinuosity, the stronger the non-linear characteristics.

2.2 Calculation of Urban Form Parameters

2.2.1 Study Area

This study focuses on the Mong Kok district of Hong Kong as its primary research subject. Located in the heart of the Kowloon Peninsula, Mong Kok is one of the world's most densely populated areas and Hong Kong's most representative high-density mixed-use commercial and residential district. The district features extremely high building density, a forest of high-rise buildings, narrow and winding streets, and a complex and variable spatial form, exhibiting the typical characteristics of a coastal high-density urban district. Additionally, Mong Kok is situated at a key node along Hong Kong's primary wind corridors. Under the influence of summer monsoons and typhoons, the internal wind environment within the district is complex, and some areas present significant wind environment hazards at the pedestrian level.



Figure 2-1 Pic of Mong Kok (Figure by author.)

The selection of the Mong Kok district holds the following representative significance: First, its high-density, high-rise building form is a typical model of coastal urban development in Asia, and the research findings have strong applicability; Second, the district features a rich variety of spatial elements, including multiple typical urban morphological characteristics such as street canyons, building clusters, and open space intersections, making it suitable for systematic research on the quantification of morphological parameters; Third, the Mong Kok area is densely populated with high pedestrian traffic and frequent commercial activity; pedestrian level wind environment issues directly impact public safety and urban resilience, making them of significant practical importance. The specific boundaries of the study area are delineated by the red dashed lines shown in Figures 2 - 7. This area covers the core commercial district of Mong Kok and its surrounding major streets, with a total area of approximately 0.5 square kilometers. It includes major thoroughfares such as Nathan Road, Sai Yeung Choi Street, and Fa Yuen Street, as well as a large number of secondary streets and alleys. The selection of this area fully considers the integrity of the district's functions, the rationality of boundary conditions, and the efficient utilization of computational resources, ensuring that the study area is representative of the typical characteristics of the Mong Kok district while facilitating systematic numerical simulations and morphological parameter

analysis.

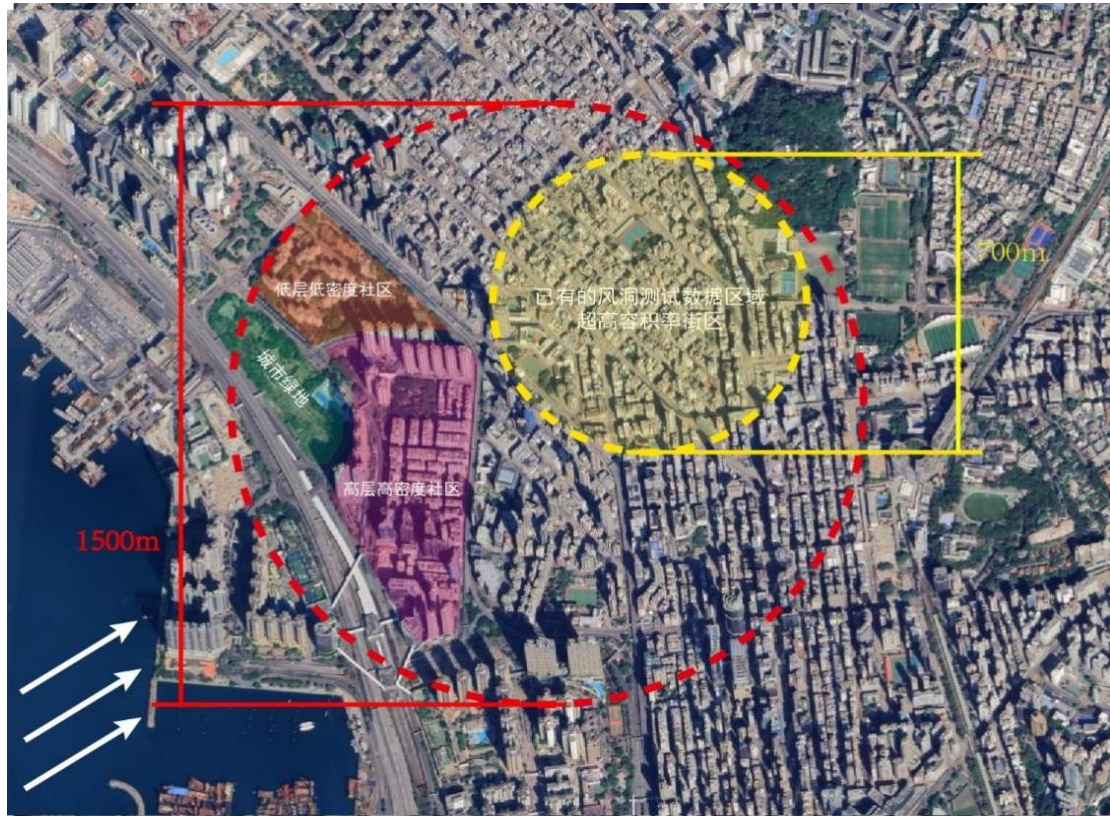


Figure 2-2 Study Area (Figure by author.)

2.2.2 Data Preprocessing

In studies of pedestrian wind environments at the urban block scale, the academic community typically defines all ground-level open areas (including roads, plazas, public green spaces, and other non-built spaces) as components of the urban wind tunnel system. As the primary pathways for urban ventilation, the spatial morphological characteristics of these open spaces directly influence the distribution patterns and intensity variations of the wind field. In this study, in addition to its inherent spatial complexity, the Mong Kok neighborhood also features numerous additional elements such as temporary structures, street stalls, and outdoor advertising installations, which further increase the complexity of the actual wind environment.

To avoid excessive complexity in the study subject and ensure a focused research focus, this study performed necessary simplifications on the original floor plan of the Mong Kok neighborhood. The simplification process primarily involved removing temporary structures and attachments, consolidating scattered outdoor facilities, and regularizing irregular building

boundaries. The purpose of this simplification was to concentrate the research focus on the influence mechanism of the core building fabric at the block level on wind field distribution, eliminating interference from secondary factors, and thereby more clearly revealing the intrinsic relationship between urban morphological parameters and wind environment safety.

Figure 2-2 displays the spatial texture map of the Mong Kok neighborhood following simplification. The delineation of this study area comprehensively considered the functional integrity of the neighborhood, the rationality of boundary conditions, and the efficient utilization of computational resources. The simplified block texture map retains the most essential spatial morphological characteristics of Mong Kok, including key elements such as building floor plans, the spatial orientation of major streets, and the spatial relationships among building clusters, providing reliable baseline data for subsequent quantitative calculations of urban morphological parameters. Based on this simplified Mong Kok block texture map, this study will systematically conduct quantitative calculations and analyses of various urban morphological parameters



Figure 2-3 Building forms within the study area (Figure by author.)

2.2.3 Extraction of Open Centerlines

In the quantitative analysis of the aforementioned morphological parameters, key indicators such as street width (W), building spacing (D), street directionality (R), and street curvature (S) all require systematic calculations based on road centerlines. As a skeletal element of the urban open space system, the accurate extraction of road centerlines has a decisive impact on the precision of subsequent morphological parameter quantification. For the simplified spatial model of the Mong Kok neighborhood, this study employs an automated extraction method based on the Euclidean Allocation algorithm to identify and generate centerlines for the complex open space network within the neighborhood.

The core principle of the Euclidean Allocation algorithm lies in calculating the Euclidean distance from every point in space to the nearest obstacle (in this study, building boundaries) and identifying the central axis of open space based on the gradient changes in the distance field. This method offers advantages such as high computational efficiency, strong adaptability, and stable results, making it particularly suitable for high-density urban blocks like those in Mong Kok, which feature dense buildings and irregular street patterns.

The specific technical workflow begins with the definition of the study area. First, target areas requiring road centerline generation are identified, centered on predefined key locations. The delineation of these areas requires comprehensive consideration of the functional integrity of the block, the rationality of boundary conditions, and the effective allocation of computational resources. Subsequently, all open spaces within the block (including roads, squares, alleys, and other non-building areas) undergo high-precision rasterization. This study employs a grid resolution of 0.1 meters. This setting effectively captures the spatial characteristics of Mong Kok's narrow alleys while striking a good balance between computational efficiency and accuracy. The choice of grid resolution directly affects the level of detail in centerline extraction; a grid that is too coarse will lose important spatial information, while one that is too fine will significantly increase the computational load.

After completing the rasterization process, the algorithm proceeds to the core stage of distance field calculation. For the rasterized open spaces, the Euclidean distance from the center point of each grid cell to the nearest building boundary is calculated individually. This

step generates a continuous distance field, where areas with larger distance values represent the center positions of open spaces farther from building boundaries, while areas with smaller distance values are closer to building boundaries. The generation of the distance field provides the foundational data for subsequent centerline extraction. Based on the Euclidean distance field, the Watershed Algorithm or local maximum detection methods are employed to identify the central axes of open spaces. Specifically, the algorithm searches for local maximum paths within the distance field; these paths represent the positions in open spaces that are farthest from the building boundaries on both sides, conforming to the geometric definition of road centerlines. Within the complex spatial fabric of the Mong Kok district, this step effectively identifies the centerline networks of major streets, minor streets, and narrow alleys.

After identifying the centerline positions, the boundaries of the identified centerline regions must be extracted, and the raster-format centerline data must be converted to vector format through vectorization processing. Finally, the extracted centerline data undergoes topological relationship checks and optimization, including breakpoint connections, correction of hanging segments, and handling of self-intersecting loops. This step ensures that the final centerline network possesses good connectivity and integrity, providing a reliable data foundation for subsequent calculations of morphological parameters based on network topology.

This study strictly confines the aforementioned computational process to the research boundaries of the Mong Kok district, performing a systematic centerline extraction of the district's entire open space system. The resulting centerline network for Mong Kok's open spaces is shown in Figures 2 - 3. This network clearly illustrates the complex street fabric of the Mong Kok district, including the centerlines of major thoroughfares such as Nathan Road and Sai Yeung Choi Street, as well as those of numerous secondary streets and narrow alleys. This centerline network provides a reliable spatial reference for the subsequent quantitative calculation of key morphological parameters, such as street width, building spacing, street directionality, and street curvature.



Figure 2-4 Building centerlines within the study area (Figure by author.)

2.2.4 Calculation and Analysis of Urban Morphological Parameters

After determining the calculation methods and completing the centerline extraction, this study divided the Mong Kok district of Hong Kong into 7,161 30×30 m grid cells as the basic computational units. For each grid cell, this study used Python scripts to calculate 11 urban morphological parameters (C, Hm, HV, FAR, D, W, S, SVF, FAI, λ_b , SLOPE) and set five different calculation range sizes (30 m, 50 m, 75 m, 100 m, and 150 m) for each parameter to systematically investigate the sensitivity of these parameters to grid size.

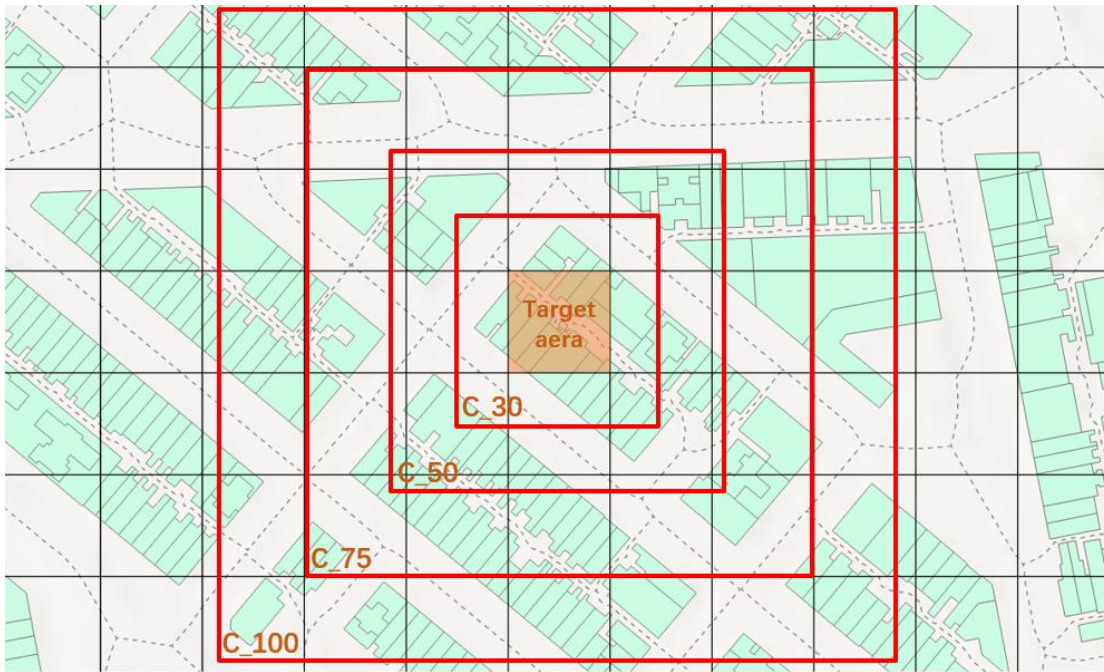


Figure 2-5 Schematic of the computational domain (Figure by author.)

Specifically, the calculation process first performs grid-by-grid calculations for parameter C (open space coverage). Within each 30×30 m grid cell, the proportion of open space is calculated for five different radius ranges—30 m, 50 m, 75 m, 100 m, and 150 m—centered on the grid's center. Subsequently, the same procedure is repeated for the remaining 10 morphological parameters, including Hm (average building height), HV (coefficient of variation in building height), and FAR (floor area ratio), ensuring that each parameter yields quantified values for all five calculation radii within every grid cell. The entire calculation process is automated via Python loop scripts for batch processing, significantly enhancing data processing efficiency. Upon completion of the calculations, this study consolidated the quantified results of all morphological parameters into a CSV-formatted urban morphological parameter database. This database uses grid cells as row indices and morphological parameters along with their corresponding calculation ranges as column indices, forming a high-dimensional data matrix comprising 7,161 rows $\times$ 55 columns (11 parameters $\times$ 5 size ranges). The CSV-format database offers excellent readability and compatibility, facilitating flexible access and in-depth analysis across various software platforms (such as Python, R, and Excel). For example, Figure 2-4 shows the results visualized in ArcGIS Pro using the CSV file. It can be seen that within a 30-meter calculation radius, the parameter

"open space axis density" is significantly higher on the southern side of the analysis area, indicating weak spatial continuity and pronounced fragmentation in this region.

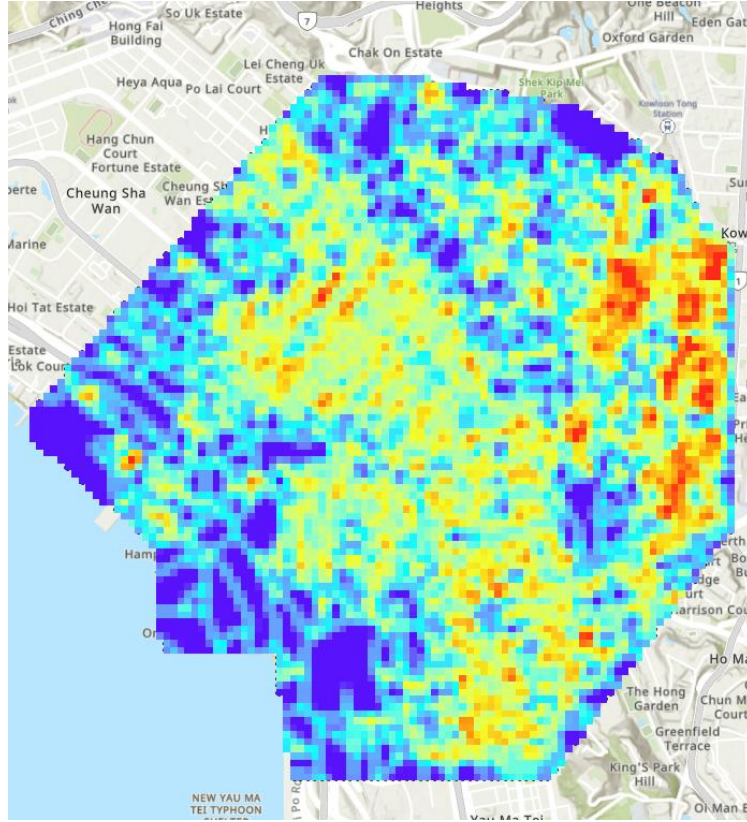


Figure 2-6 Example of urban morphology parameter calculation results: Heatmap of the calculation results for parameter D_30 (Figure by author.)

Based on the established urban morphology parameter database, this study conducted a systematic analysis of the statistical characteristics of each parameter across different grid sizes. The aim was to reveal the distribution patterns, central tendencies, and sensitivity to grid cell size of each morphological parameter, thereby providing data support for the subsequent development of pedestrian level wind environment prediction models. The specific analysis results are as follows will be shown in Appendix.

2.3 Summary of This Chapter

Through a systematic review and sensitivity analysis of urban morphological parameters, this chapter has laid a solid theoretical and methodological foundation for subsequent pedestrian level wind environment prediction models based on morphological parameters. First, regarding the construction of the urban morphological parameter system, this study

comprehensively considered key morphological elements influencing the wind environment at the urban micro-scale. From multiple dimensions — including building density, height characteristics, open space distribution, and terrain slope—it proposed ten core parameters, such as Floor Area Ratio (FAR), Building Coverage Ratio (BCR), Average Building Height (Hm), Open Space Coverage (C), Open Space Width (W), building surface area ratio (λ_b), windward area index of podiums (FAI), fragmentation index (D), and sinuosity (S). These parameters not only quantitatively describe the geometric characteristics of urban space but, more importantly, reflect the potential regulatory mechanisms of urban form on airflow dynamics, providing an operational approach for translating urban design language into computable wind environment assessment elements.

Regarding parameter extraction methods, this study established a technical framework combining raster sampling with directional analysis, tailored to the spatial attributes of different parameters. For non-directional morphological parameters (such as FAR, BCR, and Hm), spatial discretization sampling was performed using square grids of five sizes ranging from 30 to 150 meters, generating a total of 7,161 sampling units covering the entire Mong Kok district. This multi-scale parameter extraction strategy maximizes the retention of spatial heterogeneity information in urban morphology while ensuring computational efficiency, providing sufficient sample size for establishing statistical correlations between morphological parameters and pedestrian level wind environment indicators. The results of the computational scope sensitivity analysis reveal differences in the stability of various urban morphological parameters under varying scales; this finding provides important guidance for determining the optimal sampling scale in pedestrian level wind environment prediction models.

In summary, this chapter not only establishes a quantitative system of morphological parameters suitable for high-density urban blocks but also clarifies the scale-dependent characteristics of different parameters through systematic sensitivity assessments. The study found that for highly stable parameters, sampling at smaller scales (e.g., 30 – 50 meters) can capture local morphological features, whereas for highly sensitive parameters, larger scales

(e.g., 100 – 150 meters) should be selected to obtain stable statistical characteristics. This data-driven scale selection strategy provides a scientific basis for constructing predictive models linking morphological parameters and pedestrian level wind environment indicators in the next chapter, while also offering methodological guidance for reasonably determining spatial analysis units in wind environment assessments within urban design practice. It is worth noting that, as a typical urban form with a high-density orthogonal grid layout, the Mong Kok district's parameter stability characteristics may to some extent reflect the general patterns of regularized urban textures. However, for organically grown districts with more complex morphologies, the scale sensitivity of parameters may exhibit different patterns, which offers a direction worth exploring for future research expansion to include more urban types.

Chapter 3 PALM-4U Simulation Setup and Evaluation Metrics

This chapter aims to establish a numerical simulation benchmark for the wind environment in the Mong Kok district, providing reliable data support for subsequent pedestrian level wind environment prediction models based on urban morphological parameters. The Parallel Large Eddy Urban Model (PLAM-4U) is adopted as the core computational tool. Based on the Large Eddy Simulation (LES) method, this model can explicitly resolve large-scale eddy structures within the urban canopy. Compared to the traditional Reynolds-Averaged Navier-Stokes (RANS) method, it offers significant advantages in capturing transient gust events and flow characteristics around complex building clusters. This chapter first systematically elaborates on the theoretical foundations and numerical methods of the PALM-4U model, followed by a detailed introduction to the construction process of the Mong Kok neighborhood geometric model, computational domain setup, meshing strategies, and boundary condition configurations.

To ensure the reliability of the simulation results, this chapter places particular emphasis on the validation of the urban wind field simulation. By incorporating benchmark data from wind tunnel experiments led by The Chinese University of Hong Kong, an accuracy analysis of different inflow configurations was conducted to ultimately determine the optimal combination of simulation parameters. The validation process employs a multi-level evaluation system: comparing wind speed profiles in the vertical direction and verifying wind speed distributions at pedestrian height in the horizontal direction, while using quantitative metrics such as the Mean Absolute Percentage Error (MAPE) and Root Mean Square Error (RMSE) to comprehensively assess model performance. Building on this foundation, this chapter further establishes an indicator system for pedestrian level wind environment assessment, laying the methodological groundwork for the Mong Kok-wide simulation in Chapter 4 and the predictive model development in Chapter 5. The work in this chapter will ensure that the wind environment data used in subsequent research possesses sufficient scientific rigor and reliability.

3.1 PALM-4U Model Overview and Applicability Analysis

3.1.1 Basic Principles of Large-Scale Turbulence Simulation

Large Eddy Simulation (LES) is a turbulence simulation method that lies between the Reynolds-Averaged Navier-Stokes (RANS) method and Direct Numerical Simulation (DNS). The RANS method involves time-averaging the Navier-Stokes equations to solve only the statistical averages of the flow field. Although it offers high computational efficiency, it cannot capture the transient flow characteristics dominated by turbulent fluctuations. The DNS method, on the other hand, directly solves all turbulent structures from large-scale to dissipative scales. While it provides high accuracy, its computational cost is extremely high, making it difficult to apply to engineering-scale studies of urban wind environments. The LES method is based on the theory of turbulence energy levels. Its core concept is that large-scale vortices carry the majority of the turbulence energy and are significantly influenced by boundary conditions and flow field geometry, exhibiting anisotropic characteristics; whereas small-scale vortices primarily serve a dissipative role, with relatively uniform structures and statistical isotropy. Based on this understanding, LES uses spatial filtering to decompose turbulent motion into two components: the resolvable scale and the sub-grid scale. Large-scale vortex structures larger than the filtering scale are solved directly via governing equations to accurately reproduce the unsteady evolution of the flow field; while small-scale vortices below the filtering scale are parameterized using sub-grid models to characterize their dissipative and transport effects on large-scale motion.

In the field of urban wind environment research, the value of the LES method lies in its ability to analyze the transient characteristics and complex vortex structures of the flow field. Unlike the RANS method, which can only provide average wind speed distributions, LES can directly simulate the time-dependent evolution of airflow, accurately outputting transient indicators closely related to pedestrian safety—such as gust intensity and turbulence fluctuations—thereby effectively identifying the risk of sudden strong winds that may occur under specific urban morphological conditions. Furthermore, for complex flow phenomena commonly found in high-density urban blocks—such as building flow, street canyon

turbulence exchange, and corner vortices—the LES method, with its ability to directly resolve large-scale vortices, can more accurately reflect the interaction mechanisms between urban morphology and the near-surface wind field. It is precisely because of the balance LES achieves between computational accuracy and engineering feasibility that this method has become a crucial technical tool in current research on urban microclimate and wind environments, providing a reliable physical foundation for subsequent pedestrian level wind environment assessments based on numerical simulations.

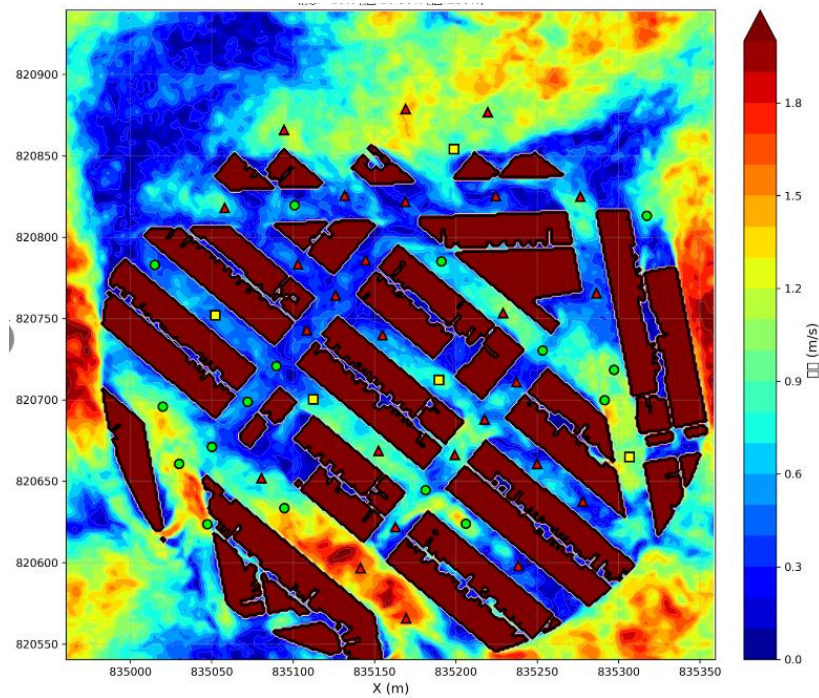


Figure 3-1 Large-Eddy Simulation (LES) wind field diagram for a building
(Figure by author.)

3.1.2 PALM-4U Model Architecture and Features

The computational platform adopted in this study is PALM-4U (PALM for Urban Applications), a large-eddy simulation model developed by the University of Hannover, Germany, specifically for complex urban environments based on the PALM (Parallelized Large-eddy Simulation Model). Compared to general-purpose commercial fluid dynamics software, PALM-4U possesses significant architectural advantages in addressing urban-scale wind environment problems. First, the model employs an orthogonal Cartesian grid system combined with the Immersed Boundary Method (IBM) to handle complex building geometries. This approach avoids the issues of declining mesh quality and low generation

efficiency faced by traditional conformal meshing when dealing with high-density, diverse urban building clusters. It enables the rapid and relatively accurate conversion of GIS urban geographic data into computational models, effectively preserving the mechanical turbulence excitation of airflow by building edges.

Second, PALM-4U has been extensively optimized for large-scale parallel computing environments, enabling efficient utilization of up to thousands of CPU cores for collaborative computation. This capability allows for long-term simulations of urban blocks spanning hundreds of meters at extremely high spatial resolutions (e.g., 1–2 meters), thereby capturing the micro-scale gust details critical to pedestrian safety. Furthermore, the model incorporates a comprehensive set of urban physical process parameterization schemes, including a vegetation canopy model and a surface energy balance model. The vegetation model realistically simulates the drag resistance and turbulence dissipation effects of street trees and urban green spaces on airflow through a leaf area density (LAD) parameterization method; meanwhile, the radiation and energy balance module offers expansion potential for future studies on thermally buoyancy-driven mixed convection. In summary, PALM-4U, with its efficient grid processing technology, powerful parallel computing capabilities, and specialized urban physics modules, is an ideal tool for conducting pedestrian level wind environment assessments in high-density urban blocks.

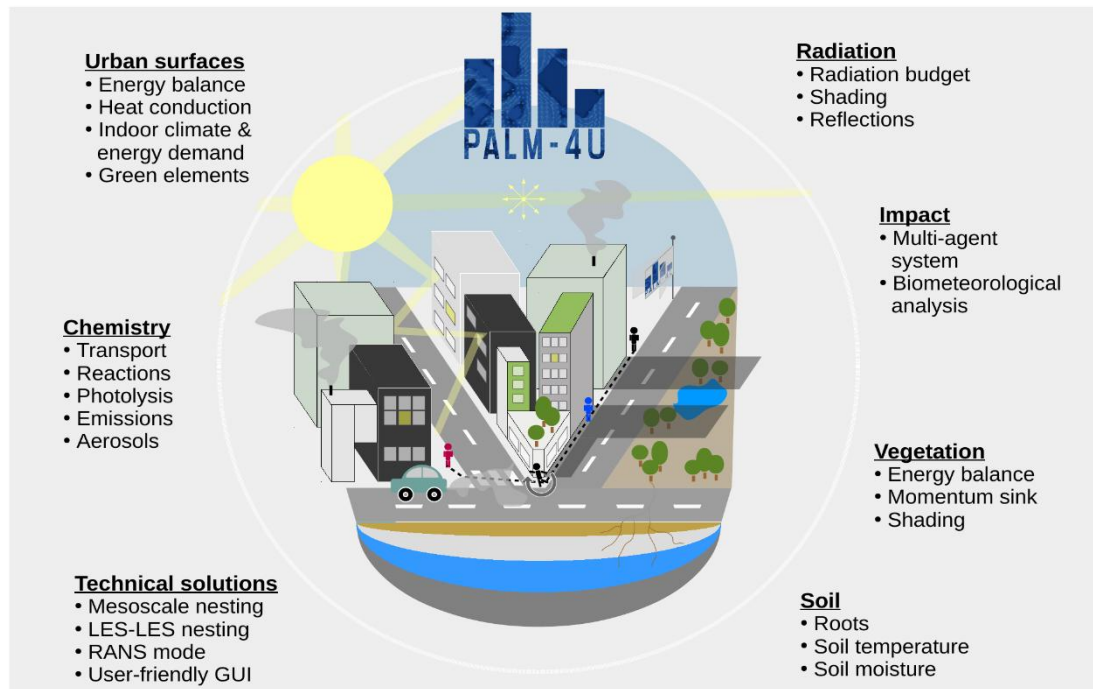


Figure 3-2 Introduction and Capabilities of the PALM-4U Model (Source:

https://palm.muk.uni-hannover.de/trac/attachment/wiki/palm4u/skizze_mosaik_plus_text.png)

3.1.3 Analysis of the Applicability of Large Eddy Simulation (LES) in Pedestrian level wind environment Assessments

In selecting a method for simulating the urban wind environment, this study employs Large Eddy Simulation (LES) rather than the traditional Reynolds-Averaged (RANS) method, primarily based on considerations of the “instantaneous” and “extreme” characteristics inherent in pedestrian level wind environment assessments. Traditional RANS methods, by time-averaging the Navier-Stokes equations, primarily focus on the statistical average state of the flow field. Although this method has lower computational costs and can reasonably predict average wind speed distributions, its inherent assumption of time averaging inevitably filters out transient pulsation information from the flow field. However, in actual pedestrian level wind environment assessments, it is often not the average wind speed but sudden, intense gusts that cause pedestrians to fall or objects to be blown away. By directly analyzing large-scale vortex structures that carry the majority of turbulent kinetic energy, the LES method can fully reproduce the time-dependent evolution of the flow field. This enables the accurate calculation of key statistical parameters, such as gust factors and standard deviations of wind speed, thereby revealing the risks associated with extreme gusts that are masked by

the RANS method.

Furthermore, for areas like Mong Kok in Hong Kong—a typical region characterized by the coupling of high-density high-rise buildings with complex topography—the LES method offers irreplaceable advantages in analyzing complex flow mechanisms. Airflow within high-density blocks is significantly influenced by building geometry and exhibits distinct unsteady characteristics, such as periodic vortex shedding at building corners and intermittent turbulent exchange within street canyons. The RANS method, which is typically based on the assumption of isotropic eddy viscosity, struggles to accurately simulate these large-scale anisotropic turbulent structures, often leading to prediction errors regarding the extent of separation zones and local wind speed extremes. In contrast, LES models only small-scale dissipative vortices while directly calculating large-scale motion strongly influenced by boundary conditions. Consequently, it can more accurately capture the mutual interference effects between terrain-induced flow deflection and flow around building clusters. This high-fidelity analysis of complex unsteady flow fields provides a solid physical foundation for accurately identifying pedestrian level wind environment hazards within urban blocks.

In summary, PALM-4U, with its efficient mesh processing, powerful computational capabilities, and specialized urban physics modules, has become the ideal tool for conducting pedestrian level wind environment studies in high-density urban blocks.

```

#-----#
palmsrun                                     Thu 19 Mar 2026 03:02:42 AM EDT
Version: PALM 24.04

called on:                                cat
config. identifier:                       default (execute on IP: 127.0.0.1)
running in:                              interactive run mode
number of cores:                          16
tasks per node:                           16 (number of nodes: 1)

cpp directives:                           -cpp -D__gfortran -D__parallel -DMPI_REAL=MPI
                                           DOUBLE_PRECISION -DMPI_2REAL=MPI_2DOUBLE_PRE
                                           CISION -D__netcdf -D__rmtmg -D__fftw
compiler options:                         -Ofast -ffree-line-length-none -I /opt/progra
                                           m/gnu_13.3/netcdf-c-4.8.1/include -I/opt/prog
                                           ram/gnu_13.3/fftw-3.3.8/include -I/root/palm_
                                           model_system-master/packages/palm/model/lib/r
                                           rmtmg/lib/include
linker options:                           -Ofast -ffree-line-length-none /opt/program/g
                                           nu_13.3/netcdf-c-4.8.1/lib/libnetcdf.so -L/o
                                           pt/program/gnu_13.3/fftw-3.3.8/lib -lfftw3 -L
                                           /root/palm_model_system-master/packages/palm/
                                           model/lib/rmtmg/lib/lib/ -lrmtmg

run identifier:                           jyht_v29
activation string list:                   d3#
#-----#

>>> everything o.k. (y/n) ? y

```

Figure 3-3 PALM-4U model code interface (Figure by author.)

3.2 Wind Tunnel Experimental Reference Data

This study was supported by the research team led by Assistant Professor He Yueyang at The Chinese University of Hong Kong, which provided critical data from wind tunnel experiments conducted in 2023 targeting the Mong Kok district of Hong Kong. The wind tunnel experiments selected the Mong Kok district as a representative high-density urban block for study, and a scaled physical model was constructed based on real GIS building base maps to ensure the reliability of the geometry and block morphology. The model was printed at a scale of 1:400 and mounted on a rotatable turntable to simulate different inflow directions and compare scenarios. The test area at the center of the turntable had a diameter of approximately 0.875 m, with multiple measurement points uniformly distributed within this area. These points were categorized into three groups—parallel, perpendicular, and oblique—based on their orientation relative to the street for statistical analysis. Prior to model setup, the obstruction ratio was calculated and recorded for each design scenario. For standard models, the obstruction ratio was less than 5%; scenarios where local high-rise buildings

caused the obstruction ratio to slightly exceed 5% were noted separately in the records. Photographs and floor plans of all models and measurement point locations are shown below:

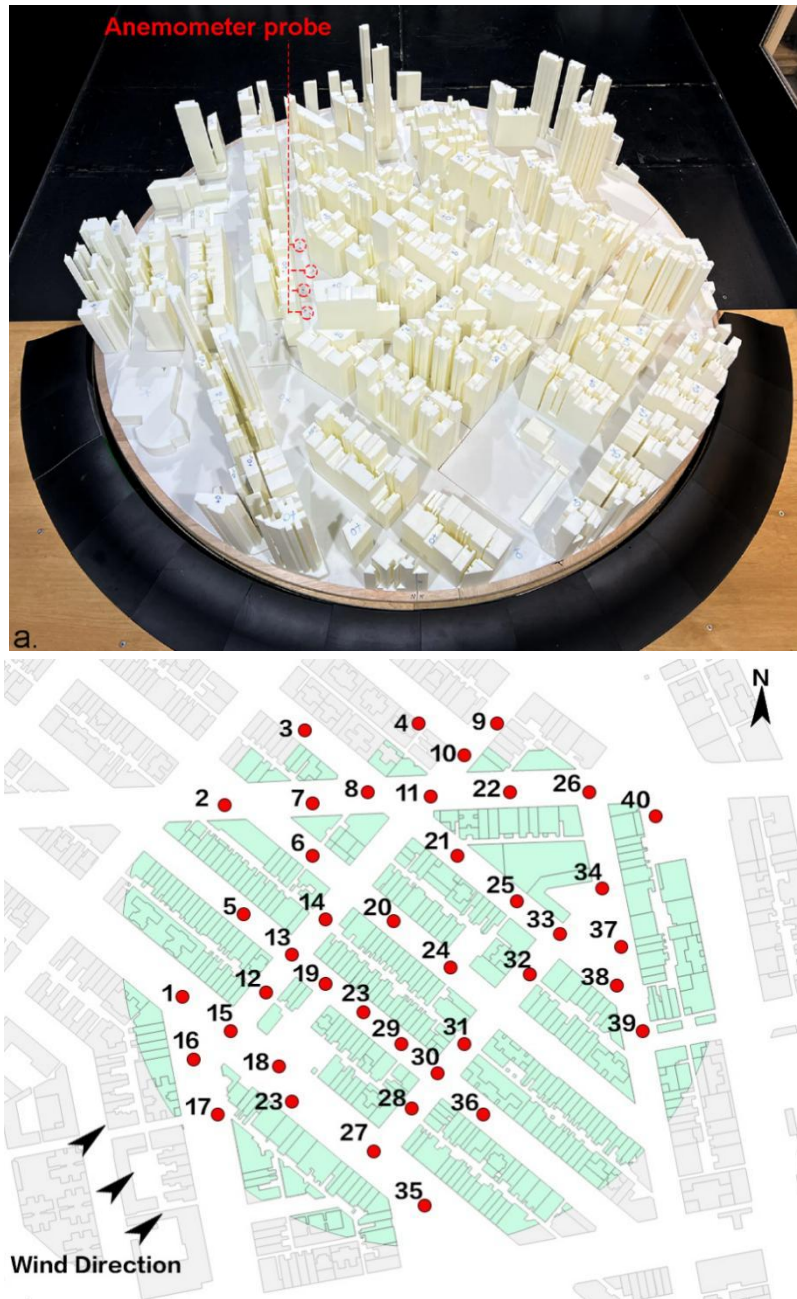


Figure 3-4 Wind tunnel experiments in the Mong Kok district of Hong Kong

(Source: He Yueyang, CUHK)

The experiments were conducted in a large low-speed wind tunnel, utilizing multi-channel thermal anemometers and hot-wire anemometers for pedestrian-level point measurements and profile validation, respectively. All thermal anemometers were calibrated at the wind tunnel inlet using known wind speeds prior to each test, and the calibration

coefficients were recorded; During formal measurements, each measurement point was sampled at a frequency of 10 Hz for 30 seconds (approximately 301 samples per point), and measurements were repeated for all points in a predetermined sequence after the flow field stabilized to ensure comparability. During the experiments, representative inflow vortices were generated by arranging roughness elements and adjustable panels upstream; where necessary, hot-wire anemometers were used to validate the turbulence intensity profile. The final data collected includes: raw time series for each measurement point ($10 \text{ Hz} \times 30 \text{ s}$), average wind speed, standard deviation, turbulence intensity, maximum/minimum values, calibration coefficients for the corresponding probes, blockage ratio, and model geometric parameters for each scenario; based on these data, the rate of wind speed change between scenarios and comfort classification statistics can be calculated.

3.3 Computational Domain Construction and Mesh Generation

3.3.1 Construction of the Mong Kok District Geometric Model

The construction of the geometric model is the foundation for conducting high-fidelity large-eddy simulation, and its accuracy directly determines the reliability of the flow field analysis. To ensure that the simulation results can be directly compared and validated against wind tunnel experimental data, this study strictly replicated the Mong Kok block test model used by the Wind Tunnel Laboratory of the School of Architecture at The Chinese University of Hong Kong within the PALM-4U platform. The simulation area covers the exact same geometric scope as the wind tunnel experiments, featuring typical high-density, high-rise urban characteristics.

Based on the geometric data of the experimental model provided by The Chinese University of Hong Kong, this study utilized ArcGIS to construct a full-scale digital geometric model. To maintain a high degree of consistency with the wind tunnel test conditions, the model preprocessing followed the same simplification principles as those used in the construction of the wind tunnel scale model: the main building outlines and volumetric characteristics were retained, potential topological errors in the digital model were corrected, and small ancillary components (such as small billboards and canopies) that have a negligible

impact on the flow field at the block scale were removed. Furthermore, since wind tunnel experiments are conducted on a flat turntable and do not incorporate real-world topographic variations, this study similarly adopted a flat ground surface assumption in the numerical model and did not incorporate Digital Elevation Model (DEM) data. This approach was taken to eliminate the interference of topographic factors on the flow field, ensuring strict correspondence between the numerical simulation and the physical wind tunnel experiments in terms of boundary conditions, thereby focusing on evaluating the accuracy of PALM wind environment simulations for high-density building forms.

3.3.2 Computational Domain Setup and Static Driver Generation

To avoid the interference of computational domain boundary effects on the flow field in the core study area, this study strictly adhered to the best practice guidelines for urban wind environment simulation published by the Architectural Institute of Japan (AIJ) and the European Organization for Scientific and Technological Cooperation (COST) when setting the computational domain dimensions. Horizontally, the computational domain covers the core block of Mong Kok and a sufficient buffer zone around it to allow for the full development of inflow turbulence and the natural dissipation of wake flows; vertically, the height is set to more than twice the height of the tallest building in the area to prevent non-physical compression of the urban canopy flow at the top boundary.

Regarding the meshing strategy, this study employs an orthogonal Cartesian grid system based on the PALM-4U core. In the pedestrian height range (1.5 m to 2 m above ground level) and in key physical process zones around buildings, a high-resolution uniform grid (with a mesh size of $1\text{ m} \times 1\text{ m} \times 1\text{ m}$) is used to accurately resolve complex turbulent structures such as corner vortices and separation bubbles within street canyons. In the vertical direction, a stretched grid technique is applied starting from the area above the building canopy, with the grid spacing gradually increasing with height. This ensures computational accuracy near the ground while effectively controlling the total number of grid cells, thereby optimizing the allocation of computational resources. Finally, the processed building geometry, terrain elevation, and land use type data were integrated, and a static driver file was generated using the PALM preprocessing program. This file not only defines the physical boundary conditions

for the simulation but also includes the distribution of surface roughness parameters based on morphological analysis, providing complete static environmental input for subsequent unsteady large eddy simulations.



Figure 3-5 Plan view of the PALM simulation model (Figure by author.)

3.4 Boundary Conditions and Parameter Configuration

The configuration of boundary conditions in large eddy simulation directly affects the accuracy and convergence of flow field calculations. Based on the requirements for reproducing wind tunnel experiments and the characteristics of the PALM-4U model, this study systematically configured the computational domain boundary conditions, initial flow field state, and turbulence perturbation scheme.

3.4.1 Boundary Condition Settings

3.4.1.1 Horizontal Boundary Conditions

Considering the spatial characteristics of the Mong Kok neighborhood scale relative to the atmospheric boundary layer, this study employs periodic boundary conditions for the horizontal directions (x and y) of the computational domain (with the following settings: $bc_lr = 'cyclic'$, $bc_ns = 'cyclic'$). The physical significance of periodic boundaries lies in the fact that after the fluid flows out from one side of the computational domain, it re-enters from the opposite side with the same flow field state, thereby simulating the continuous effect of the

infinitely extending urban fabric on the airflow. This setting offers two advantages in urban wind environment simulations:

First, periodic boundaries eliminate the non-physical effects that may be introduced by manually setting inflow/outflow boundary conditions. Traditional inflow boundaries require the manual specification of velocity profiles and turbulence characteristics, while outflow boundaries must ensure that the gradients of flow field variables satisfy specific constraints; these settings often fail to fully align with real atmospheric conditions. By establishing a "self-consistent" flow field cycle, periodic boundaries allow turbulent structures to develop and evolve naturally within the computational domain, preventing the growth of boundary layer thickness from being truncated by the outlet boundary. Second, this configuration is suitable for studying local wind environment characteristics within high-density blocks. As a typical representative of the core area of Hong Kong's Kowloon Peninsula, the Mong Kok block is similarly surrounded by continuous, high-density urban built-up areas. Periodic boundaries implicitly assume statistical homogeneity of the block's geometry in the horizontal direction, which generally aligns with the similar building density and height distribution characteristics of Mong Kok and its neighboring areas, thereby reasonably simulating the modulating effect of regional urban roughness on the boundary layer wind field.

3.4.1.2 Vertical Boundary Conditions

The vertical boundary uses a standard configuration: the bottom boundary is set as a no-slip wall, while the top boundary is set as a free-slip condition, combined with a Rayleigh damping layer to absorb upward-propagating gravity waves and prevent their non-physical reflection at the top boundary.

The bottom boundary is treated using the wall function approach built into PALM-4U. This method is based on the Monin-Obukhov similarity theory, which establishes a velocity gradient relationship between the surface and the center of the first grid layer through a logarithmic wall function, thereby avoiding the extremely high grid resolution required for direct analysis of the viscous boundary layer. The surface roughness length z_0 , as a key parameter of the wall function, directly controls the attenuation characteristics of near-surface

wind speeds. In this study, z_0 is initially set to 0.001, a value corresponding to a typical smooth, flat surface (such as the turntable base in wind tunnel experiments). In subsequent validation steps, this parameter will be refined through systematic comparison with wind tunnel experimental data to accurately reproduce the effective roughness effects in high-density urban areas.

3.4.1.3 Turbulence Generation Strategy

To accelerate the transition from the initial state to statistical steady state, this study enabled the PALM random force disturbance scheme (set code: `create_disturbances = .TRUE.`). This scheme artificially excites turbulence pulsations by periodically superimposing random velocity disturbances onto the flow field (disturbance application interval set to: `dt_disturb = 150.0 s`), thereby shortening the time required for turbulence to evolve from the laminar initial field to a fully developed turbulent state. The disturbances are primarily applied within the boundary layer at the top of the building canopy and above it, ensuring that turbulent energy can rapidly cascade into small-scale vortex structures, accelerating the flow field's attainment of statistical equilibrium. This technique is widely adopted in large-eddy simulation and can significantly reduce the simulation time required to reach quasi-steady-state conditions, thereby improving computational efficiency.

3.4.2 Initial Conditions and Wind Profile Settings

3.4.2.1 Initial Flow Field Configuration

The simulation employs the constant profile initialization method (set code: `initializing_actions = 'set_constant_profiles'`), which involves uniformly applying a predefined vertical wind speed profile across the entire computational domain as the initial flow field. This method has a clear physical interpretation and is suitable for urban boundary layer simulations under neutral atmospheric conditions. In this study, the atmospheric boundary layer is set to a neutral state (setting code: `neutral = .TRUE.`), meaning buoyancy effects caused by temperature stratification are neglected. Additionally, the humidity transport module is disabled (setting code: `humidity = .FALSE.`) to focus on the dynamics dominated by mechanical turbulence. This simplifying assumption is consistent with the isothermal conditions of wind tunnel experiments, ensuring the comparability of the numerical

simulation and physical experiments in terms of thermodynamic boundary conditions.

3.4.2.2 Wind Speed Profile Parameterization

The vertical distribution of wind speed is defined by discretized height-velocity data pairs (uv_heights and u_profile/v_profile). Based on the inflow velocity profiles measured in wind tunnel experiments, this study sets the velocity components in the u and v directions at 17 characteristic heights. The specific configuration is as follows:

Sampling heights (uv_heights): 0.0, 0.8, 1.2, 2.0, 4.0, 6.0, 8.0, 10.0, 16.0, 26.0, 50.0, 76.0, 100.0, 126.0, 150.0, 176.0, 200.0 meters, for a total of 17 layers. Sampling points are densely distributed near the ground (0–10 meters) to accurately capture the wind speed gradient near pedestrian height; above 10 meters, the spacing gradually widens, consistent with the physical characteristic that the wind speed profile of the atmospheric boundary layer changes more slowly at higher altitudes. u-direction velocity profile (u_profile): The velocity at the ground level is 0 (satisfying the no-slip condition); at a height of 0.8 meters, the velocity is 1.380 m/s, gradually increasing with height to reach 5.156 m/s at 200 meters. This profile conforms to the logarithmic or power-law distribution characteristics of the atmospheric boundary layer. Velocity profile in the v direction (v_profile): The values are identical to those of the u profile, indicating that the incoming wind direction is from the southwest ($u = v$). This wind direction setting aligns with the turntable angle configuration used in wind tunnel experiments and represents the prevailing wind direction in the Hong Kong region during summer.

Furthermore, this study did not employ geostrophic wind driving ($\omega = 0.0$, i.e., the Coriolis force parameter was set to zero). This setting implies that the flow field is maintained solely by the equilibrium between the initial profile and surface drag, without considering the deflection effects caused by Earth's rotation. For neighborhood simulations with horizontal scales below the kilometer level, the influence of the Coriolis force can be neglected, and this simplification aligns with standard practices in micro-scale wind environment research.

3.4.2.3 Vertical Grid Stretching Strategy

To ensure computational accuracy in the pedestrian height zone while controlling the

total number of grid cells and reducing overall computation time, this study employs a layered stretched grid strategy in the vertical direction. The specific parameter configuration is as follows: Stretch start height (`dz_stretch_level`): 110.0 meters. Areas below this height use a 1-meter grid with equal spacing to ensure that flow field details in the building canopy and pedestrian activity layers are fully resolved. Meanwhile, the stretching factor (`dz_stretch_factor`) is set to 1.15. Above the starting height, the grid height of each layer increases by a factor of 1.15 to achieve a smooth transition. The maximum grid height (`dz_max`) is set to 20.0 meters. The single-layer mesh height after stretching is limited to no more than 20 meters to avoid numerical dissipation caused by overly coarse grids in the upper atmosphere. Through this strategy, a total of 206 vertical grid layers ($nz = 206$) are established. Given a total computational domain height of approximately 450 meters, this approach ensures a high-resolution simulation with 1-meter resolution near the ground while effectively reducing computational load through vertical stretching, thereby achieving a balance between accuracy and efficiency.

3.4.2.4 Verification of the Physical Rationality of Parameter Settings

The aforementioned boundary conditions and initialization scheme were not chosen arbitrarily but were based on the following physical considerations: the periodic boundary and neutral layer boundary assumptions align with the idealized environment of wind tunnel experiments; the southwest-facing inflow reproduces the dominant wind characteristics of the Hong Kong region; and the layered mesh strategy achieves a 1-meter resolution at pedestrian height, meeting the spatial accuracy requirements for pedestrian level wind environment assessment. The final code configuration with all parameters is as follows:

```
&initialization_parameters
! ===== Mesh Settings =====
  nx = 399, ny = 399, nz = 1, dx = 1.00,
  dy = 1.00, dz = nz=1,
! ===== Initialization =====
initializing_actions = 'set_constant_profiles',
neutral = .TRUE.,
humidity = .FALSE.,
```

```

! ===== Boundary Conditions =====
bc_lr = 'cyclic',
bc_ns = 'cyclic',
! ===== Solver and Topography =====
psolver = 'multigrid',
topography = 'read_from_file',
! ===== Roughness =====
roughness_length = 0.35,
! ===== Extended wind profile =====
uv_heights = 0.0, 0.8, 1.2, 2.0, 4.0, 6.0, 8.0, 10.0, 16.0, 26.0, 50.0, 76.0, 100.0, 126.0,
150.0, 176.0, 200.0,
u_profile = 0.0, 1.380, 2.141, 2.280, 2.934, 2.918, 3.044, 2.988, 3.318, 3.306, 3.684,
3.861, 4.238, 4.485, 4.713, 4.941, 5.156,
v_profile = 0.0, 1.380, 2.141, 2.280, 2.934, 2.918, 3.044, 2.988, 3.318, 3.306, 3.684,
3.861, 4.238, 4.485, 4.713, 4.941, 5.156,
/
&runtime_parameters
! ===== Runtime =====
&runtime_parameters end_time = 7199.9,
skip_time_data_output = 5459.9,
dt_data_output = 60.0,
! ===== Disturbances =====
create_disturbances = .TRUE.,
dt_disturb = 150.0,
! ===== Data Output =====
data_output = 'u_xy', 'v_xy', !
section_xy = 1 !
/

```

```

Further information can be found at
https://docs.palm-model.com/24.04/Reference/LES_Model/Logging/#PAC0203

03:02:50 -start---- initializing indoor model
03:02:50 -finished- initializing indoor model
    --- informative message ---
    ID: PCM0012 generated by routine "pcm_init":

    LAD profile is omitted at building grid points which have been artificially created by the topography filtering

    Further information can be found at
    https://docs.palm-model.com/24.04/Reference/LES_Model/Logging/#PCM0012

03:02:51 -start---- calculating view factors for radiation interaction
03:03:19 -finished- calculating view factors for radiation interaction
03:03:19 -start---- initializing surface layer
03:03:19 -finished- initializing surface layer
03:03:19 -finished- model initialization
    +++ warning message ---
    ID: PAC0192 generated by routine "do_topo_and_surface_setup":

    Topography and surface-setup output requires parallel netCDF. No output file will be created.

    Further information can be found at
    https://docs.palm-model.com/24.04/Reference/LES_Model/Logging/#PAC0192

03:03:19 -start---- surface model spinup time-stepping
03:16:42 -finished- surface model spinup time-stepping
03:16:42 -start---- netcdf_define_header 3d
03:16:42 -finished- netcdf_define_header 3d
03:16:43 -start---- time-stepping

[X] 97.9 left 09:24:07 -start---- netcdf_define_header 3d
09:24:07 -finished- netcdf_define_header 3d
[XXXXXXXXXXXXXXXXXXXX] 70.0 left

```

Figure 3-6 PALM simulation interface (Figure by author.)

3.5 Simulation Validation and Sensitivity Analysis

To ensure the accuracy and reliability of the numerical simulation results, this study incorporates wind tunnel experimental data as a reference (Ground Truth) to systematically verify and validate the key physical parameters of the PALM-4U model. The calibration process follows a logical workflow of “profile fitting—parameter inversion—error verification,” aiming to eliminate systematic deviations between the numerical model and the physical model regarding boundary layer characteristics.

3.5.1 Wind Tunnel Experimental Reference Data

The model calibration in this study is based on a wind tunnel experimental dataset provided by the Environmental Laboratory of the School of Architecture at The Chinese University of Hong Kong. This dataset contains two types of key observational data: First, the vertical wind profile: a reference boundary layer profile measured at the center of the wind tunnel turntable, uninfluenced by the building model. This profile reflects the background flow field characteristics under experimental conditions and serves as the basis for deriving the inlet boundary condition parameters for the simulation. Second, pedestrian-level wind data: actual measurements from sensors deployed at key locations within and around the Mong Kok district model. These measurement points cover typical spatial configurations such as street canyons, street corners, and open plazas, and are used to ultimately evaluate the predictive

accuracy of the numerical simulation results.

3.5.2 Determination of the Roughness Parameter (z_0)

In atmospheric boundary layer simulations, the surface roughness length (z_0) is a key parameter that determines the form of the logarithmic law distribution of near-surface wind speeds. This study initially attempted to invert the vertical wind speed profiles measured in wind tunnel experiments using a nonlinear least-squares method combined with the logarithmic law equation, yielding a fitted value of approximately $z_0 = 0.35$ m. However, preliminary simulation validation revealed that when $z_0 = 0.35$ m was used as the surface roughness input for PALM-4U, the simulated wind speeds at pedestrian height (1.5 m) were significantly lower than the measured values from wind tunnel experiments, and the near-surface wind speed gradient exhibited excessively strong dissipative characteristics. Upon in-depth analysis, this deviation was primarily attributed to the special boundary conditions of the wind tunnel experiments: the experiments were conducted on a smooth turntable surface, whose physical roughness is far lower than that of a real urban surface. Directly using the z_0 value derived from high-altitude profiles (which reflect the comprehensive roughness of upstream urban blocks) to define the local surface wall function resulted in an artificial overestimation of surface drag, thereby causing excessive momentum loss in the near-surface layer. To address this issue, this study conducted tests with a significant downward adjustment of z_0 , following the recommendations in the official PALM documentation regarding smooth wall simulations. Sensitivity analysis results show that when z_0 is reduced to **0.001 m** (approaching the physical properties of a smooth plane), the model's performance in the near-surface flow field improves significantly, and the agreement between the wind speed distribution and experimental data reaches its best. Therefore, this study ultimately revised the parameter settings, adopting $z_0 = 0.001$ m as the surface roughness parameter for the formal simulation to accurately reproduce the smooth surface conditions of the wind tunnel experiments.

3.5.3 Comparative Experiments with Different Inflow Configurations

Based on the established physical parameters, this study further conducted a sensitivity analysis on the driving methods for the inflow boundary. Comparative tests were performed

on the two common driving mechanisms in urban large-eddy simulations: the Surface Geostrophic Driver and the Fixed Profile Driver (Dirichlet). The test results show that although the geostrophic driver can theoretically maintain boundary layer self-equilibrium, in the specific scenario of this study, the equilibrium profile generated by this method does not fully match the specific inflow profile measured in wind tunnel experiments (particularly the complex near-surface shear characteristics), leading to systematic deviations across the entire height range. In contrast, the fixed-profile driver can enforce the inlet boundary conditions, ensuring a high degree of consistency between the inflow wind field and experimental values.

However, the main challenge faced by fixed profile driving in application is the issue of momentum loss during flow field development: as the airflow passes through the computational domain, it is affected by surface friction (even at low z_0), causing near-surface wind speeds to gradually decay, resulting in wind speeds at pedestrian height in the target block generally being lower than the inlet set values. To address this issue, this study implemented a manual compensation strategy for near-surface wind speeds. Specifically, within the inlet boundary conditions, a nonlinear positive gain correction is applied to the input wind speed in the near-surface height range (0–100 m) to preemptively compensate for the expected frictional losses along the flow path.

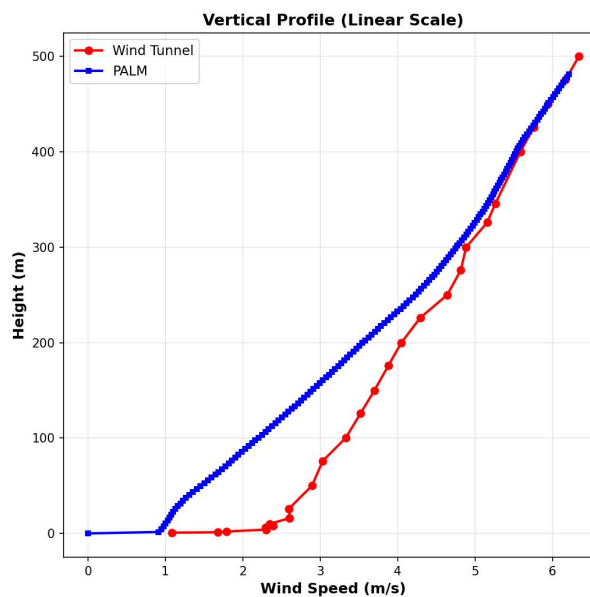


Figure 3-7 Comparison of the uncorrected wind profile with the wind tunnel wind profile

(Figure by author.)

Final validation indicates that the combined approach of “fixed profile driving + near-surface wind speed compensation,” coupled with the aforementioned corrected surface roughness parameter ($z_0 = 0.001$), successfully resolved the issue of underestimated wind speeds at pedestrian height. This approach not only ensures numerical stability but also significantly improves the correlation coefficient and coefficient of determination between simulation results and wind tunnel experimental data, outperforming the geostrophic wind driving scheme.

3.6 Validation of Simulation Results

In numerical simulation studies, validation is a critical step to confirm whether the computational results accurately reflect physical processes. It should be clarified that the core objective of this study is not to precisely reproduce the absolute wind speed values at each measurement point within the wind field, but rather to accurately simulate the spatial distribution of the wind field—that is, to identify the relative spatial relationships between high-wind-speed and low-wind-speed zones. This research focus stems from the practical needs of pedestrian level wind environment assessment: in urban design practice, planners are more concerned with "which areas are at risk of strong winds" rather than "the exact wind speed value at a specific measurement point." Therefore, the validation strategy of this study focuses on examining the correlation between simulated and measured values and the consistency of their trends, prioritizing the accurate capture of wind field patterns as the primary evaluation criterion.

3.6.1 Evaluation Metrics and Validation Methods

Based on the aforementioned research focus, this study selected four statistical indicators—Pearson correlation coefficient, coefficient of determination, root mean square error, and mean absolute error—to construct a validation framework. The Pearson correlation coefficient (R) is used to measure the degree of linear correlation between simulated and observed values, directly reflecting the model's ability to capture the spatial distribution of wind fields. When R approaches 1, it indicates that the trends in the simulated results are highly consistent with those in the observed data, meaning the model can accurately identify

which areas have relatively high wind speeds and which have relatively low wind speeds—a core capability required for pedestrian level wind environment assessment. The coefficient of determination (R^2) characterizes the extent to which simulated values explain the variation in observed values. A higher R^2 value indicates that the model can explain a larger proportion of the spatial variation in wind speed, and that the model provides a more complete depiction of the wind field heterogeneity caused by complex urban morphology. Root Mean Square Error (RMSE) is used to quantify the overall level of deviation between simulated and measured values. Because errors are squared during its calculation, it is highly sensitive to large errors and can effectively reveal whether there are significant local deviations in the simulation. Mean Absolute Error (MAE) reflects the average deviation between simulated and measured values. Compared to RMSE, it is less sensitive to outliers and provides a more robust assessment of the overall error level.

3.6.2 Validation of Wind Speed at Pedestrian Height

The wind field distribution at pedestrian height is the core focus of this study and serves as the direct basis for pedestrian level wind environment assessment. This study selected multiple key measurement points within the Mong Kok district model that cover various spatial configurations, including street canyons, street corners, the leeward sides of buildings, and open plazas. The hourly average wind speeds output by PALM-4U were systematically compared with measured data from wind tunnel experiments.

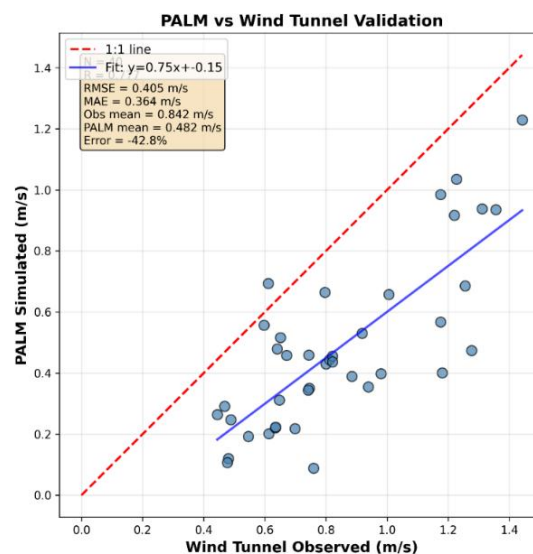


Figure 3-8 Validation of Simulation Results (Figure by author.)

Scatter plot analysis shows that the simulated values and measured values exhibit a significant positive correlation, with data points distributed around the 1:1 diagonal line. Calculations show that the Pearson correlation coefficient (R) between the two reaches 0.777, indicating that the model effectively captures the spatial distribution of the wind field—specifically, the relative positions of high- and low-wind-speed zones align closely with the measured results. The coefficient of determination (R^2) exceeds 0.6, meaning the model explains over 60% of the spatial variation in wind speed, thereby demonstrating the effectiveness of PALM-4U in simulating wind field conditions in complex, high-density urban blocks. At the same time, the validation results also show a root mean square error (RMSE) of 0.405 and a mean absolute error (MAE) of 0.364, indicating a certain numerical deviation between the simulated and measured values, with the simulated wind speeds generally exhibiting a systematic underestimation.

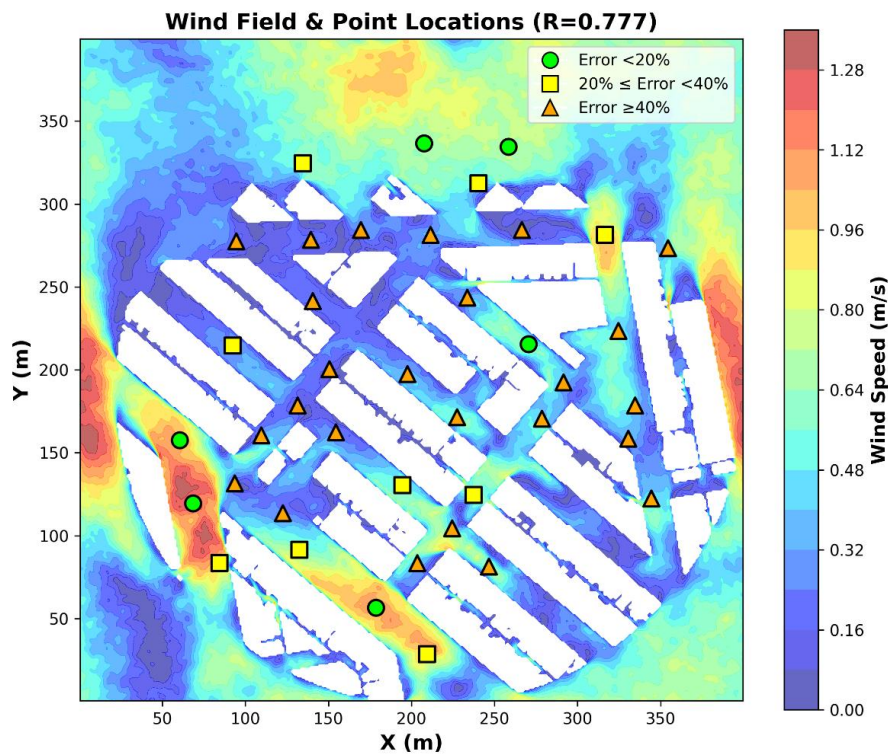


Figure 3-9 Simulation Results (Figure by author.)

3.6.3 Analysis of Simulation Deviations and Model Applicability

Regarding the aforementioned phenomenon of systematically underestimated simulated wind speeds, this study conducted an in-depth analysis by referring to the official PALM technical documentation and relevant literature. The research found that the primary cause of

this deviation can be attributed to the coupling effect between grid resolution and building surface roughness. The grid resolution adopted in this study is $1\text{ m} \times 1\text{ m}$, which means that the building surface is discretized into a step-like grid structure at one-meter intervals within the numerical model. Compared to the finely machined, smooth, and continuous physical model surfaces used in wind tunnel experiments, the building boundaries in the numerical model inevitably exhibit a higher effective roughness. From a fluid dynamics perspective, this discretized stepped surface excites additional small-scale turbulent vortex structures within the building boundary layer, significantly enhancing the turbulent dissipation effect in the near-wall region. According to the theory of turbulent energy levels, these additionally excited small-scale vortices draw energy from large-scale motion and convert it into thermal energy through viscous dissipation, ultimately leading to a reduction in time-averaged kinetic energy in the pedestrian height region, manifested as a systematic underestimation of wind speed. This phenomenon has been widely recognized by researchers in the field of Large Eddy Simulation (LES) and represents an inherent limitation of the immersed boundary method when handling complex building geometries under finite mesh resolution constraints.

Despite the aforementioned systematic bias in absolute wind speeds, the PALM-4U simulations in this study performed exceptionally well in identifying the spatial patterns of the wind field. A correlation coefficient (R) of 0.777 clearly demonstrates that the model accurately captures the local acceleration and deceleration trends in airflow caused by complex building geometries: In areas where wind tunnel measurements indicated high wind speeds—such as primary ventilation corridors, street canyon exits, and building corners—the simulation results similarly exhibited relatively high wind speed values; conversely, in areas where measurements indicated low wind speeds—such as the leeward sides of buildings and enclosed courtyards—the simulation results also demonstrated corresponding wind speed attenuation characteristics. In summary, although the PALM-4U simulations in this study exhibit a systematic underestimation of absolute wind speeds, they demonstrate sufficient reliability in identifying high-risk pedestrian level wind environment zones and capturing the spatial distribution patterns of wind fields. Given that the core objective of this study is to

establish a correlation model between urban morphological parameters and pedestrian level wind environment risk locations, the current simulation accuracy is fully capable of meeting the requirements for subsequent pedestrian level wind environment assessment and predictive model development.

3.7 Pedestrian level wind environment Evaluation Index System

The core of pedestrian level wind environment assessment lies in establishing reasonable wind speed classification thresholds. Internationally, widely adopted pedestrian wind environment evaluation systems—represented by the Lawson standard and the Davenport comfort criteria^[88]—are based on the human physiological response to wind, classifying wind speeds into three levels: comfortable, uncomfortable, and hazardous. Building upon this framework and referencing the Hong Kong Planning Department's 'Feasibility Study on Air Circulation Assessment'^[89]—a specialized study on pedestrian wind environments in Hong Kong's high-density urban areas. This study, which integrates local climatic characteristics with urban morphology, sets the safety threshold for pedestrian wind speed at **15 m/s**, concluding that exceeding this value exposes pedestrians to personal safety risks such as loss of balance and falls—this review of pedestrian wind environment evaluation standards, this study adopts the following three-tier classification system:

Table 3-1 Wind Speed Classification

Grade	Wind Speed Range	Pedestrian Safety Status
Low Risk	≤ 8.0 m/s	Comfortable for walking; pedestrian activity is not significantly affected
Moderate risk	8.0–15.0 m/s	Walking feels difficult; take precautions against the wind; not suitable for prolonged outdoor activities
High risk	> 15.0 m/s	Pedestrians are at risk of losing their balance; this is a safety hazard zone

The **8.0 m/s** threshold corresponds to the lower limit of Beaufort Scale Force 5 (moderate gale), marking the critical transition point where pedestrians move from "slight

discomfort" to "marked discomfort" and is adopted by numerous studies on pedestrian wind environments as the boundary between comfort and discomfort. **15.0 m/s** corresponds to Beaufort Scale 7 (Gale), which is recognized as the critical wind speed for pedestrian safety in mainstream international evaluation standards.

3.8 Summary of This Chapter

This chapter systematically elaborates on the numerical simulation method for the wind environment in the Mong Kok district based on the PALM-4U model, providing a reliable foundation of flow field data for the subsequent development of pedestrian level wind environment prediction models.

At the numerical methodology level, this chapter provides a detailed introduction to the basic principles of Large Eddy Simulation (LES) and the technical features of the PALM-4U model. Compared to traditional Reynolds-averaged methods, LES uses spatial filtering to decompose turbulent motion into resolvable and sub-grid scales, directly solving for large-eddy structures that carry the majority of turbulent kinetic energy. This approach can more accurately capture the complex, unsteady flow field characteristics in high-density urban environments. As a Large Eddy Simulation platform specifically developed for urban applications, PALM-4U has become an ideal tool for conducting block-scale pedestrian level wind environment studies, thanks to its immersed boundary method for handling complex building geometries, its efficient parallel computing architecture, and its comprehensive urban physical parameterization scheme. At the model configuration level, this chapter details the construction process of the Mong Kok block geometric model, computational domain setup, meshing strategy, and boundary condition configuration scheme based on the requirements for reproducing wind tunnel experiments. A systematic sensitivity analysis was conducted regarding roughness parameters and inflow driving methods. Ultimately, a combined approach was adopted featuring a smooth wall roughness $z_0 = 0.001$, coupled with fixed profile driving and near-surface wind speed compensation, effectively resolving the issue of underestimated wind speeds at pedestrian heights. In terms of model validation, this chapter conducted a quantitative evaluation of the PALM-4U simulation results using wind tunnel

experimental data as a reference. The validation results indicate that the Pearson correlation coefficient (R) between simulated and measured values reached 0.777, with a coefficient of determination (R^2) exceeding 0.6, demonstrating that the model can accurately capture the spatial distribution of the wind field. Although the simulated wind speeds exhibit a systematic underestimation due to the influence of grid resolution and the discretization of building surfaces, the model performs excellently in identifying the relative spatial relationships between high-wind-speed and low-wind-speed zones, fully meeting the research requirements for pedestrian level wind environment assessment.

Regarding risk classification, this chapter references the research findings of Lawson & Penwarden and the Hong Kong Planning Department's AVAS to establish pedestrian level wind environment evaluation criteria with three risk levels—low, medium, and high—using 8.0 m/s and 15.0 m/s as classification thresholds. These criteria are grounded in clear international standards and demonstrate local applicability. This lays the methodological foundation for the flow field characteristic analysis and predictive model development in subsequent chapters.

Chapter 4 PALM-4U Simulation Process and Results

4.1 Construction and Simulation of the Global Model

To comprehensively assess the high-wind environmental characteristics for pedestrians in the Mong Kok district of Hong Kong, this study, following the series of validations in Section 3.5, used the same Large Eddy Simulation (LES) parameter configuration and expanded the computational domain to cover the entire real-world block encompassing the core area of Mong Kok. This global model is bounded by Fa Po Street to the east, Hoi Fai Road to the west, Prince Edward Road to the south, and Sham Shui Po to the north, extending approximately 2,700 meters in both the east-west and north-south directions, fully encompassing Mong Kok's typical high-density building clusters, complex street networks, and diverse urban morphological features. The geometric construction of the full-area model is based on high-precision 2.5D GIS building data provided by a research team at The Chinese University of Hong Kong. After data cleaning and format conversion, the data was imported into the PALM-4U static drive file generation workflow. The model comprises approximately 7,990 buildings, ranging in height from low-rise podiums of 5 meters to super-high-rise residential towers exceeding 150 meters, with an average building density of over 65%, representing a typical subtropical coastal ultra-high-density urban form. To accurately reproduce topographic effects.

Figure 4-1 Overall study area and the validation area from Chapter 3 (Figure by author.)

The operation of the PALM-4U model relies on a comprehensive set of input driver files, among which static driver files (Static Driver) serve as the core input files describing the physical characteristics of the urban land surface within the simulation domain. Unlike dynamic driver files, static driver files contain spatial and geographic information that does not change over time during the simulation process. They encompass various land surface attributes, including topography, building geometry, land cover types, vegetation distribution, and the proportion of impervious surfaces, and are a prerequisite for the model to correctly resolve the near-surface airflow structure within the urban canopy.

building plan contours (`buildings_2d`), building height (`building_height`), building ID (`building_id`), vegetation type (`vegetation_type`), land surface coverage classification (`nsurface_fraction`), and impervious surface classification (`pavement_type`), among others.

The Mong Kok district of Hong Kong is located in the central part of the Kowloon Peninsula, and its built environment exhibits a high degree of three-dimensional complexity: building heights range from low-rise structures with a few stories to super-tall buildings exceeding several dozen stories, and the highly irregular urban fabric creates numerous street canyons and a varied skyline. At the same time, Mong Kok is situated on a flat alluvial plain with minimal macro-topographic variation; however, at the local micro-topographic level, the guiding effect of artificial topographic features—such as elevated pedestrian bridges, sunken plazas, and podium platforms—on the near-surface wind field cannot be overlooked. Therefore, accurately representing the refined three-dimensional urban morphology of Mong Kok's blocks in static drive files is a critical technical aspect for high-quality simulation.

4.1.2 Generation of Static Files

This study calibrated high-precision 2.5D urban data for Hong Kong and generated static files. The resulting static drive files comprehensively capture the three-dimensional spatial characteristics of the ground surface in the Mong Kok district. In terms of the spatial distribution of building heights, the study area exhibits significant heterogeneity: the average building height is approximately 58.3 m, with a standard deviation of 34.1 m. The tallest buildings (super-high-rise structures in the Mong Kok commercial district) exceed 180 m in height, while the shortest buildings (old tenement buildings) are only about 10–15 m tall. This extreme heterogeneity in building height directly contributes to the complexity of the turbulent flow structure within the Mong Kok district and serves as the physical basis for this study's focus on the morphological parameter of building height variability (HV). In terms of the spatial distribution of land cover, impervious surfaces (building bases + road pavements) account for 92.3% of the total area within the study domain, while green vegetation accounts for only 5.8% (mainly concentrated in Mong Kok Park and the tree-lined strip along Nathan Road), water bodies account for 0.4%, and the remainder consists of unclassified areas. The

highly dense impervious surface coverage serves as the physical basis for the intense urban heat island effect and complex wind field structure observed in the Mong Kok neighborhood.

The static input file for the Mong Kok district accurately reflects the actual three-dimensional urban morphology of the study area, meeting the input data quality requirements for PALM-4U high-resolution large-eddy simulation, and can serve as a reliable foundation for subsequent simulations.

4.1.3 PALM Urban Wind Environment Simulation Input Settings

The computational grid employs uniform meshing technology, with a consistent fine resolution of $3\text{ m} \times 3\text{ m} \times 3\text{ m}$ across the entire computational domain. This ensures accurate capture of complex flow fields in street spaces with concentrated pedestrian activity and around buildings. This grid size allows for the thorough analysis of key flow characteristics, such as vortex structures within street canyons, separated flow at building corners, and the passage effect between building clusters. In the vertical direction, to optimize computational resource allocation while maintaining computational accuracy, this study employs a layered mesh approach: below 225 meters (covering all buildings and their wake influence zones), a uniform vertical resolution of 3 meters is maintained; in the free atmosphere above 225 meters, a vertically stretched grid with gradually increasing resolution is employed, with the maximum stretch ratio controlled within 1.15 to effectively reduce computational load while avoiding the accumulation of numerical errors. The total number of grid cells across the entire computational domain has been optimized to meet the resolution requirements of Large Eddy Simulation (LES) for turbulent characteristic scales while remaining within an acceptable computational cost range. The boundary conditions strictly follow the optimized configuration scheme systematically validated in Chapter 3. The inflow boundary conditions employ a wind profile-driven approach based on measured data: this study references the work by Lo et al., which obtained the true vertical distribution of wind speeds in the Hong Kong region under typhoon conditions through the inversion of meteorological observation station and sounding data^[38]. This study extracted the wind profile data from that literature and used it as the velocity profile input for the inflow boundary on the western side of the computational domain. Compared to traditional logarithmic or power-law wind profiles, this setup more

closely approximates the actual wind field conditions in the coastal areas of Hong Kong during strong wind weather, significantly enhancing the authenticity and applicability of the simulation results. Cyclic boundary conditions were applied to both the northern and southern sides of the computational domain. This approach has been demonstrated in the validation study in Chapter 3 to effectively simulate the infinite extension of the urban canopy, thereby eliminating artificial interference from the side boundaries on the flow field within the core computational region. A Rayleigh damping layer is applied at the top of the computational domain. By gradually increasing the momentum dissipation term within approximately 200 meters of the top, this effectively suppresses the reflection of gravity waves—generated by terrain and buildings—at the top boundary after their upward propagation, ensuring the physical authenticity of the flow field in the vertical direction. The simulation duration is set to 5 minutes of physical time, with the first 5 minutes serving as the spin-up period. Once the turbulence statistics reach a quasi-steady state, a turbulence statistical analysis is performed on the flow field data at the final time step. All data outputs use pedestrian height ($z = 1.5$ m) as the primary sampling layer, with a horizontal resolution of 3 meters and spatial coverage of the entire computational domain, providing a comprehensive data foundation for subsequent pedestrian level wind environment assessments and correlation analysis of morphological parameters.

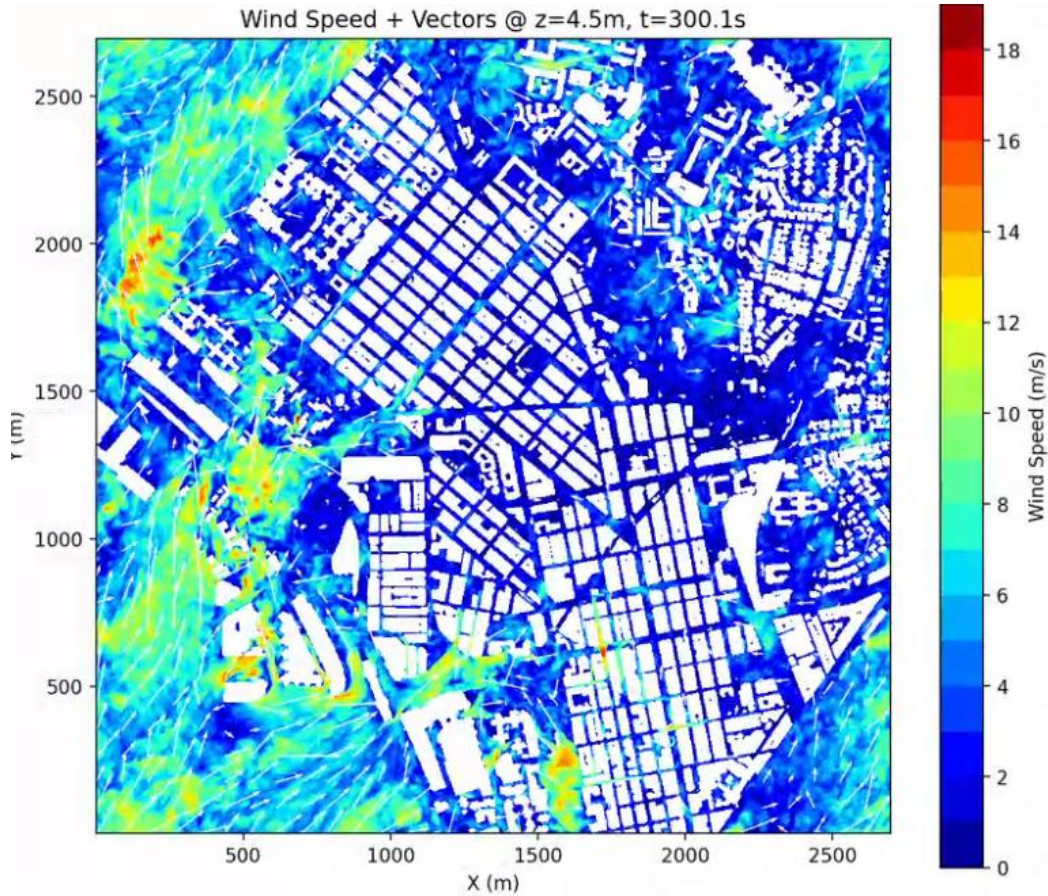


Figure 4-2 Urban wind field map of the Mong Kok district under strong southeasterly convective weather (Figure by author.)

4.1.4 Simulation Results

The full-domain simulation was run on a desktop workstation equipped with an AMD Ryzen 3950X central processing unit, utilizing 16 computing cores for parallel processing; the simulation duration for a single wind direction was approximately 12 hours. Simulation outputs included key physical quantities such as instantaneous three-dimensional wind speed fields and average wind speed fields, with a total data volume exceeding 20 GB. Based on these high-resolution flow field data, this study was able to systematically analyze the wind environment characteristics of the Mong Kok district under real-world urban morphological constraints, identify high-risk pedestrian level wind environment zones, and provide sufficient sample data support for the establishment of the morphological parameter prediction model in Chapter 5.

Since wind directions during severe convective weather are often chaotic and lack a clear prevailing direction, this study summarizes and aggregates the results of wind field

simulations for all eight wind directions. At each monitoring point, the maximum wind speed value recorded across all eight wind directions is calculated and designated as the maximum wind speed for that point, and a maximum wind speed distribution map is plotted. The maximum wind speed distribution map is shown in Figure 4-3.

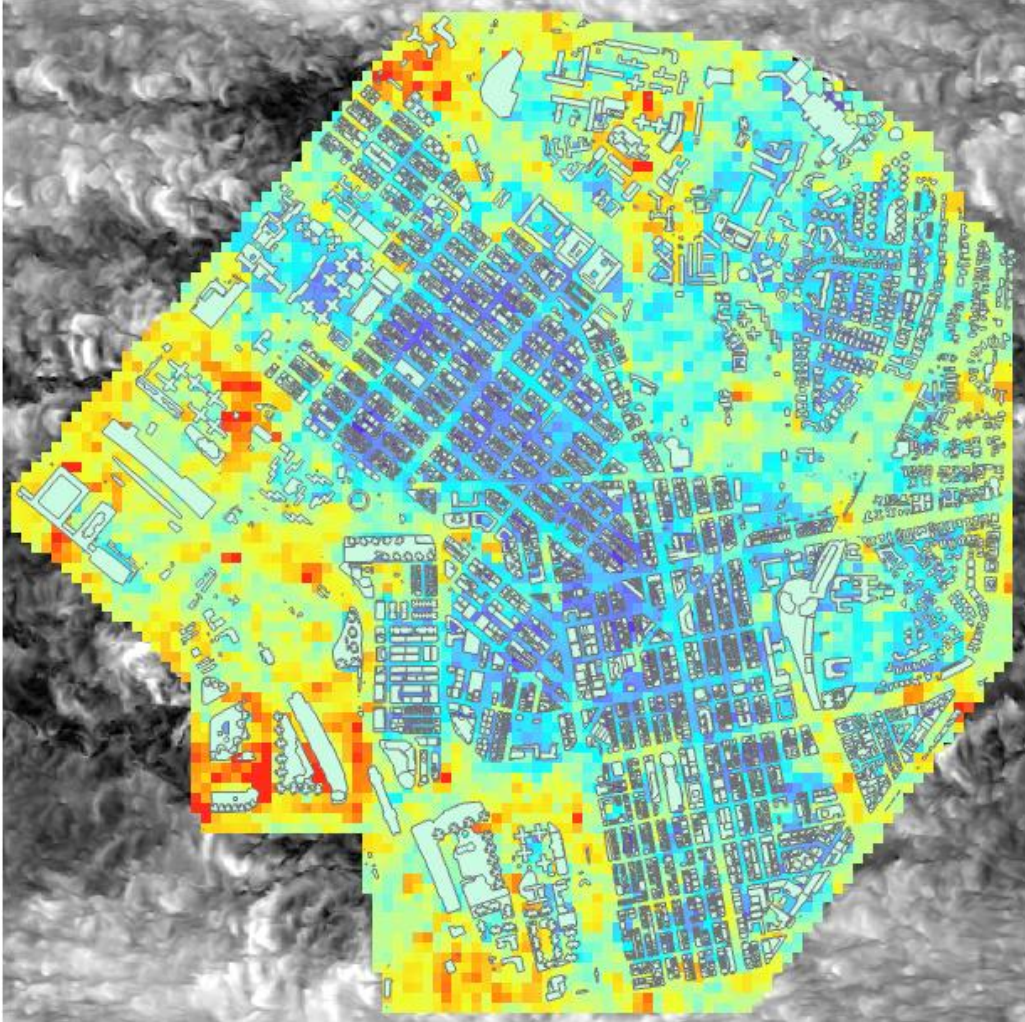


Figure 4-3 Statistics on locations of strong winds in urban horizontal wind fields under severe convective weather (Figure by author.)

4.2 Overall Characteristics of the Wind Environment at Pedestrian Height

4.2.1 Wind Speed Distribution

Based on the maximum wind speed results at pedestrian height (1.5 m) from 7,161 30 m $\times$ 30 m grid points obtained via PALM-4U simulation, the overall wind environment characteristics are as follows: The maximum wind speeds at pedestrian height in the study

area ranged from 0.000 to 20.584 m/s, with a mean of 8.743 m/s and a median of 8.696 m/s. The two values are very close (difference < 0.05 m/s), indicating that the wind speed distribution exhibits good symmetry and generally approximates a normal distribution. The standard deviation is 3.215 m/s, indicating significant spatial variation in wind speed across different plots.

In terms of quantile characteristics, the 25th percentile is 6.375 m/s, the 75th percentile is 10.946 m/s, and the interquartile range is approximately 4.571 m/s; the 95th percentile is 13.953 m/s, and the 99th percentile is 16.749 m/s, indicating that the vast majority of areas (approximately 95%) have pedestrian wind speeds below 14 m/s, while areas with extremely high wind speeds are distributed as isolated points.

4.2.2 Frequency Distribution Characteristics

Based on the frequency distribution across wind speed intervals (Table 4-1), wind speeds are concentrated in the **6–12 m/s** range, with the 8–10 m/s bracket having the highest frequency at **23.0%** (1,644 measurement points); followed by 6–8 m/s (20.8%) and 10–12 m/s (18.8%). These three ranges combined account for **62.6%** of all observation points, constituting the primary characteristic of the pedestrian wind environment in the study area.

Table 4-1 Statistical Distribution of Wind Speed at Pedestrian Height

Wind Speed Range (m/s)	Number of Monitoring Points	Percentage (%)
0 – 2	71	1.0
2–4	365	5.1
4–6	1,093	15.3
6–8	1,489	20.8
8–10	1,644	23.0
10–12	1,348	18.8
12–14	805	11.2
14–16	237	3.3
16–18	78	1.1
18–20	27	0.4
> 20	4	0.1

Measurement points in low-wind-speed zones (< 4 m/s) accounted for approximately 6.1% of the total, primarily concentrated within densely built-up, highly enclosed blocks, where wind speeds were significantly reduced due to the shielding effect of the building clusters. Measurement points in high-wind-speed zones (> 14 m/s) accounted for approximately 3.4% of the total, exhibiting a spatially localized and extremely concentrated pattern that stood in stark contrast to the surrounding areas.

4.3 Analysis of Flow Field Mechanisms in Typical High-Density Coastal Urban Settings

4.3.1 Spatial Distribution Characteristics of High-Wind-Speed Clusters

Based on an analysis of the spatial coordinates of high-risk monitoring points, the 204 high-risk points exhibit significant **spatial clustering**, primarily concentrated in two areas, both of which share the urban morphological characteristics of **coastal/near-coastal high-rise, medium-density** development.

Cluster A (coordinates approximately $X=834,000-834,550$, $Y=819,800-820,100$): This is the area with the highest concentration of extreme wind speeds in the study area, with a maximum wind speed of 20.58 m/s and a dense distribution of approximately several dozen high-risk monitoring points. This area is adjacent to the coast, with a predominantly high-rise building structure, relatively low building coverage (medium density), and wide spacing between buildings, forming several open wind tunnels. Driven by the pressure difference between the sea and land, air currents from the sea rush in at high speeds through the gaps between buildings, creating a pronounced channeling effect; simultaneously, high-altitude air currents at the tops of high-rise buildings are deflected downward by the buildings' geometry, producing a downwash effect, which further increases wind speeds at the height of pedestrians on the ground.

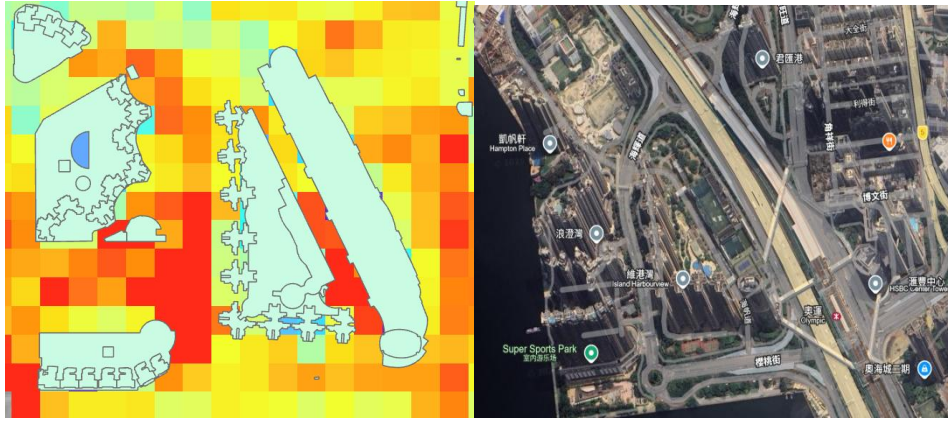


Figure 4-4 High-Risk Pedestrian level wind environment Zone A

(Figure by author., Google Earth)

Aggregation Area B (coordinates approx. $X=835,344$, $Y=821,937$): Located approximately 1.5 km from Aggregation Area A, this area also features a high-rise, medium-density building pattern, with a maximum wind speed of approximately 18.89 m/s. Its cause is similar to that of Aggregation Area A, both related to localized acceleration channels formed by high-rise buildings under conditions of moderate enclosure.

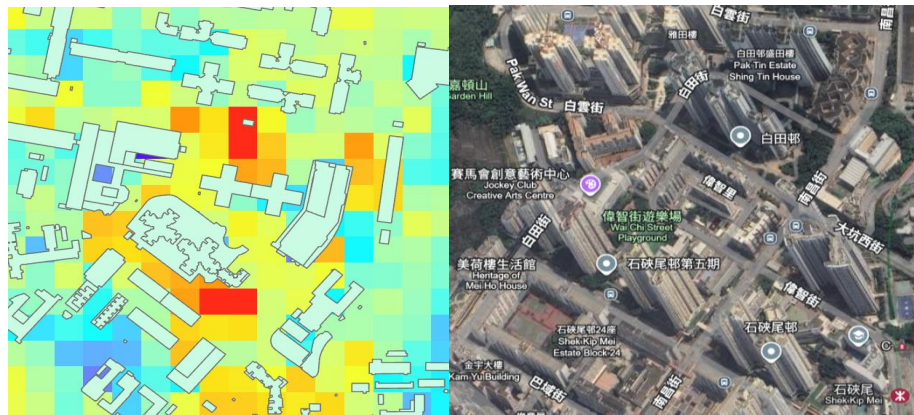


Figure 4-5 High-Risk Pedestrian level wind environment Zone B

(Figure by author., Google Earth)

A common characteristic of both clusters is that high-rise buildings provide sufficient potential energy due to their height, while the spacing between buildings resulting from moderate coverage creates the necessary channel conditions for airflow acceleration; the combination of these two factors results in extreme pedestrian wind speeds.

4.3.2 Discussion on Wind Speed Attenuation Mechanisms in High-Density Low-Rise Neighborhoods

In stark contrast to the high wind speed characteristics of the aforementioned coastal

high-rise areas, the Mong Kok area—located between the two clusters and characterized by extremely high-density low- and mid-rise buildings—exhibits significantly lower pedestrian-level wind speeds, with very few high-risk measurement points. This "counterintuitive" phenomenon is explained in this study through the following mechanisms: First, the frictional dissipation effect of high urban roughness: Mong Kok has extremely high building coverage and extremely narrow streets, creating very high urban canopy drag. As airflow passes through dense clusters of low-rise buildings, it encounters significant frictional resistance from building facades, causing kinetic energy to be continuously dissipated; by the time it reaches pedestrian height, wind speeds have already significantly decreased. This aligns with the fundamental principle in urban climatology that “high-roughness urban morphology significantly reduces near-surface wind speeds.” Secondly, low building heights suppress downwash and corner flow acceleration: Mong Kok is dominated by low- and mid-rise buildings, whose limited heights are insufficient to channel high-speed airflow from the upper atmosphere to the ground, and there is no significant corner flow acceleration effect from high-rise buildings. In contrast, coastal high-rise buildings can transport strong winds from altitudes above 100 m to the ground via downwash, whereas clusters of low-rise buildings lack this "vertical transmission channel." Finally, the relationship between street orientation and prevailing wind direction: The Mong Kok area features a dense street network with diverse orientations. When the prevailing wind direction is not fully aligned with any single street direction, airflow frequently deflects between streets, increasing momentum loss and further limiting the wind tunnel acceleration effect.

4.3.3 Comprehensive Patterns of Urban Form's Impact on Pedestrian Wind Speed

Based on the above analysis, this study proposes the following discussion regarding the wind field simulation results: the occurrence of extreme wind speeds at pedestrian height does not stem from “greater building density,” but rather from the specific combination of “potential energy from high-rise buildings + acceleration channels formed by moderate coverage.” Conversely, an extremely dense low-rise urban fabric has a significant protective effect in attenuating pedestrian wind speeds.

This conclusion resonates with the results of linear feature screening in Chapter 5: both FAR (floor area ratio, $\beta = -1.431$) and FAI (frontage area index, $\beta = -0.344$) have significant negative effects on wind speed, meaning that the higher the building density and the larger the frontage area, the lower the pedestrian wind speed; whereas Hm (mean building height, $\beta = +0.661$) makes a significant positive contribution to wind speed, indicating that building height is a key positive factor driving extreme wind speeds. Together, these findings validate the physical mechanisms underlying the aforementioned morphology-wind speed relationship.

4.4 Pedestrian level wind environment Risk Assessment Results

4.4.1 Overall Risk Level Distribution

Based on the three-tier wind speed classification criteria established in Chapter 3, pedestrian level wind environment ratings were assessed for all 7,161 monitoring points, with the results shown in Table 4-2.

Table 4-2 Distribution of Pedestrian level wind environment Levels in the Study Area

Risk Level	Wind Speed Range	Number of Monitoring Points	Percentage (%)	Corresponding Area (km ²)
Low Risk	≤ 8.0 m/s	3,018	42.1	Approx. 2.72
Medium risk	8.0–15.0 m/s	3,939	55.0	Approx. 3.54
High risk	> 15.0 m/s	204	2.8	Approx. 0.18
Total	—	7,161	100.0	Approx. 6.44

Note: Area estimates are based on each monitoring point representing a plot area of $30 \text{ m} \times 30 \text{ m} = 900 \text{ m}^2$

4.4.2 Statistical Analysis of the Spatial Distribution of Pedestrian level wind environment Indicators

The pedestrian level wind environment situation in the study area is **generally manageable but presents significant risks in certain localized areas**, as detailed below:
Low-risk zone (42.1%): Over 40% of urban plots have pedestrian wind speeds within a safe

and comfortable range. These are primarily distributed in traditional high-density neighborhoods with higher building density and stronger street enclosure, where the wind-reduction effect of building clusters is evident. **Moderate-risk zones (55.0%):** Approximately 55% of monitoring points fall within the moderate-risk range, representing the most prevalent risk level in the study area. This indicates that the pedestrian wind environment in most plots is in a state of "acceptable but requiring attention." Pedestrians in this area should reduce outdoor activities during high-wind conditions, and planning and design should prioritize the installation of wind-protection facilities. **High-Risk Zone (2.8%):** A total of 204 monitoring points (approximately 0.18 km²) exceeded the safety threshold of 15 m/s. The average wind speed in the high-risk zone reached 16.54 m/s, with an extreme value of 20.58 m/s (exceeding Beaufort Scale 8, equivalent to gale-force winds). Although high-risk zones account for only 2.8% of the total area, they are highly concentrated in specific locations, posing significant pedestrian safety hazards in certain neighborhoods. These areas should be prioritized for intervention in urban design.

4.5 Summary of This Chapter

This chapter employs high-fidelity large eddy simulation (LES) as a technical tool to conduct a systematic analysis of the physical characteristics of the high-altitude wind environment for pedestrians in the ultra-high-density urban area of Mong Kok, Hong Kong, establishing an analytical framework that spans from the development of simulation methods to the exploration of the mechanisms underlying the formation of risk zones.

In terms of simulation methodology, this chapter constructed a global PALM-4U computational model covering the core area of Mong Kok (approximately 2,700 m × 2,700 m), incorporating geometric information from 7,990 real buildings and digital elevation data. A uniform 3-meter high-resolution grid was employed, coupled with inflow boundary conditions based on measured typhoon wind profiles. After approximately 12 hours of parallel computation, three-dimensional wind speed field data covering the entire study area at pedestrian height ($z = 1.5$ m) were obtained, providing a solid physical simulation foundation for subsequent evaluations. Regarding the overall characteristics of the wind environment,

based on statistical analysis of all 7,161 measurement points, the mean maximum wind speed at pedestrian height in the study area was 8.743 m/s, with a standard deviation of 3.215 m/s. The distribution was approximately normal, concentrated in the 6–12 m/s range; The results of the three-tier risk distribution show that low-risk, medium-risk, and high-risk zones account for 42.1%, 55.0%, and 2.8% of the total study area, respectively, with extreme wind speeds reaching up to 20.58 m/s. At the level of flow field mechanisms, the study found that areas of extreme high wind speeds are concentrated in coastal zones with high-rise, medium-density buildings. The combination of vertical potential energy provided by high-rise buildings and open wind tunnels formed under conditions of moderate coverage is the fundamental cause of local extreme wind speeds; In contrast, in the extremely high-density, low-to-mid-rise traditional neighborhoods of Mong Kok, pedestrian wind speeds were significantly lower. This was attributed to the friction dissipation effect caused by the high roughness of the urban canopy, the natural suppression of downwash effects by low-rise buildings, and the multidirectional deflection and energy dissipation of airflow by the dense street network. This reveals the important principle that "high-density, low-rise urban fabric exerts a protective attenuating effect on near-surface wind speeds."

In summary, this chapter systematically establishes a physical cognitive framework for pedestrian level wind environment in the study area, clarifying the intrinsic mechanisms linking typical urban morphological elements to pedestrian wind speeds. Furthermore, the 7,161 sample points of wind speed data obtained will serve as the core training data for the predictive model in Chapter 5, bridging the methodological gap between physics-driven simulation and data-driven prediction, and providing a basis for refined pedestrian level wind environment assessment and intervention at the urban planning level.

Chapter 5 Construction of a Rapid Prediction Model for Pedestrian Wind Environment

5.1 Research Data and Wind Speed Classification Standards

5.1.1 Sample Overview

The dataset used in this study comprises 7,161 valid measurement points in the Mong Kok district of Hong Kong. Each measurement point records the maximum wind speed at pedestrian height (1.5 m above ground level) and 55 columns of urban morphological parameters (11 parameters $\times$ 5 calculation scales). The statistical characteristics of the maximum wind speed are as follows:

Table 5-1 Statistical Characteristics of Wind Field Simulation Results

Statistic	Value
Sample Size	7,161 measurement points
Mean	8.74 m/s
Standard deviation	3.22 m/s
Minimum	0.00 m/s
Median	8.70 m/s
Maximum	20.58 m/s

5.1.2 Wind Speed Classification Criteria

In Chapter 3, this study classifies the maximum wind speed at pedestrian height into three levels, which serve as the target variables for classification prediction. In the sample distribution, the "medium risk" category (8–15 m/s) accounted for the highest proportion (55.0%), indicating that more than half of the areas in the Mong Kok district are subject to restricted pedestrian activity under the influence of typhoons; the "high risk" category (>15 m/s) accounted for 2.8% (204 monitoring points) and is the primary focus of pedestrian level wind environment protection. The three-tier classification scheme ensures a more balanced sample size across categories, providing favorable conditions for the development of the prediction model.

Table 5-2 Wind Simulation Results: Pedestrian level wind environment Classification

Risk		Physical Meaning		
Level	Wind Speed Range	Sample Size	Percentage	
Low Risk	≤ 8 m/s	3018	42.2%	Comfortable for pedestrians; suitable for all outdoor activities
Moderate risk	8–15 m/s	3939	55.0%	Walking is affected; some outdoor activities are restricted
High risk	> 15 m/s	204	2.8%	Safety hazards exist; prolonged outdoor exposure is not recommended

5.2 Univariate Correlation Analysis of Urban Morphological Parameters and Wind Speed Categories

5.2.1 Spearman's rank correlation analysis

To quantitatively characterize the correlation between urban morphological parameters and pedestrian wind speed levels, this study considers both the Pearson linear correlation coefficient (r) and the Spearman rank correlation coefficient (ρ). Pearson r calculates covariance based on raw values and standardizes them; it primarily measures the strength and direction of linear correlation between two variables. It typically implies that the data are approximately continuous, the relationship is approximately linear, and it is relatively sensitive to outliers; When the relationship between variables is distinctly nonlinear, the distribution is skewed, or outliers are present, Pearson's r may underestimate the actual association or be significantly influenced by a small number of outliers. Spearman's ρ , on the other hand, first converts variables into ranks before calculating the correlation; it essentially measures whether a monotonic relationship exists between two variables (without requiring linearity) and is more robust to skewed distributions, heteroscedasticity, and outliers; When the relationship between morphological parameters and wind speed exhibits nonlinear trends—such as “initial increase followed by a plateau” or “threshold effects”—while still

maintaining a monotonic trend, Spearman's ρ is better able to stably reflect the overall association.

Given that the response of high-density neighborhood morphological parameters (such as openness and wind exposure index) to near-surface wind speed often exhibits nonlinear and threshold characteristics, and that local extreme wind speed points may appear in the sample, this study adopts Spearman's ρ as the primary indicator for univariate correlation analysis, while also reporting Pearson's r as a linear reference. A full correlation test was conducted on 55 columns of parameters (11 parameters $\times$ 5 scales), with a significance level set at $\alpha = 0.001$ (after Bonferroni correction).

5.2.2 Comparison of Significant Parameters

Among all 55 parameters, every parameter reached a significance level of $p < 0.001$, indicating that the urban form parameter system of the Mong Kok district has a general explanatory power for pedestrian wind speed. The 20 parameters with the highest absolute correlation coefficients are as follows:

Table 5-3 Analysis of the Effects of Urban Form Parameters

Rank	Parameter	Spearman ρ	Pearson r	Direction of Parameter Effect
1	FAI_30	-0.565	-0.549	Reduces wind speed
2	FAI_50	-0.558	-0.535	Reduce wind speed
3	FAI_75	-0.556	-0.539	Reduce wind speed
4	FAI_100	-0.551	-0.536	Reduce wind speed
5	FAI_150	-0.551	-0.541	Reduce wind speed
6	C_50	+0.530	+0.526	Acceleration of wind speed
7	C_75	+0.526	+0.515	Acceleration wind speed
8	C_150	+0.518	+0.506	Acceleration wind speed
9	C_100	+0.518	+0.505	Acceleration wind speed
10	λb_{30}	-0.500	-0.396	Decrease wind speed
11	FAR_30	-0.499	-0.468	Reduce wind speed
12	D_150	-0.481	-0.479	Reduce wind speed
13–15	$\lambda b_{50/75/100}$	-0.423 ~ -0.468	—	Wind speed reduction
16	SVF_150	+0.430	+0.423	Accelerated wind speed

Key Findings: FAI (Frontal Area Index) consistently ranks first in the correlation rankings across all scales, indicating that the frontal obstruction of airflow by building

clusters is the most critical protective mechanism for pedestrian level wind environment in the Mong Kok district. C (Open Space Coverage) shows a positive correlation, reflecting the wind corridor logic that "the larger the open space, the higher the wind speed."

5.2.3 Optimal Computational Scale for Each Parameter

By comparing the absolute values of Spearman's ρ for the same parameter across five computational scales, the optimal computational scale for each parameter was determined:

Table 5-4 Optimal Computational Scales for Urban Morphology Parameters and Mechanism Interpretation

Parameter	Optimal Scale	ρ	Physical Interpretation
FAI	30 m	-0.565	The blocking effect is most direct in the near field
C	50m	+0.530	Most sensitive to street-scale openness
λ_b	30m	-0.500	Local building coverage density determines shading
FAR	30m	-0.499	Areas with high floor area ratios have a strong airflow-blocking effect
D	150m	-0.481	Large-scale building density affects exposure to the background wind field
SVF	150 m	+0.430	Correlation between macro-scale openness and high-rise building clusters
Hm	30 m	-0.326	Increased building height reduces roughness and near-surface wind speed
S	50m	-0.311	Winding passages effectively attenuate the incoming flow
W	150 m	-0.288	Large-scale passage width contributes to regional ventilation
HV	30 m	-0.281	Elevation variations increase turbulent disturbances

The above results reveal an important scale-dependent pattern: different types of morphological parameters influence the wind field through distinct pathways, and consequently, the spatial neighborhoods that “best explain variations in wind speed levels” also exhibit significant differences.

On the one hand, parameters directly related to building entities (such as the frontage area index FAI, floor area ratio FAR, and building coverage ratio λ_b) show the strongest correlation at small scales (30 m), indicating that wind speeds at pedestrian height are most sensitive to the “geometry of nearby buildings.” The physical reason for this is that the building's windward projection and volumetric density within a range of several tens of meters around a pedestrian's location directly determine the energy loss and local acceleration points of the incoming flow during the processes of flow separation, obstruction, and channel constriction, thereby controlling the intensity of typical near-field mechanisms such as downwash, corner effects, and narrow-channel effects. In other words, these parameters describe “local shading and flow-guiding conditions that can be immediately perceived by pedestrians,” requiring a smaller window to capture genuine microscale differences; if averaged over a larger scale, key geometric features such as local street valleys and corners would be diluted, thereby reducing explanatory power.

On the other hand, parameters related to spatial openness (such as density/openness indices D, sky view factor SVF, and passage width W) perform better at larger scales (150 m), indicating that pedestrian wind speed levels are influenced not only by immediate buildings but also by a broader “background” context. The reason lies in the fact that these indicators reflect the overall “accessibility” and “permeability” of the urban fabric to incoming airflow at the block scale: larger open areas, continuous wide passageways, or higher SVF values typically mean that wind energy can be maintained over longer distances and transported into the interior of the block, thereby increasing local base wind speeds; Conversely, a continuous built environment characterized by high density and low SVF creates overall roughness and shielding effects over a larger area, causing background wind speeds to attenuate before entering local street valleys. Therefore, a larger computational scale is required to characterize

these cumulative effects and spatial connectivity across building blocks.

Overall, small-scale parameters emphasize “near-field obstruction and local amplification,” while large-scale parameters emphasize “exposure to the background wind field and ventilation connectivity.” This pattern of scale differentiation provides direct insights for subsequent modeling and design applications: for risk point identification and local optimization (such as at corners, intersections, and downwind areas), physical parameters at the 30-meter scale should be prioritized; whereas for the organization of wind corridors and the control of overall ventilation patterns, openness parameters at the 150-meter scale should be the primary focus.

5.3 Comparison of Significance Rankings for Urban Morphology Parameters via Multiple Linear Regression

5.3.1 Screening Method

After determining the optimal computational scales for each parameter group via Spearman analysis (yielding 10 candidate features: C_150, D_150, FAI_75, FAR_30, Hm_30, HV_30m, S_50, SVF150, W_150, λb_{30}), this study employed **the significance test of multiple linear regression (OLS)** as a second-level variable screening tool. The 10 candidate features were simultaneously included in the OLS regression model, with the maximum wind speed at pedestrian height (MAX_WIND, continuous value) as the dependent variable. A multivariate regression fit was performed on the standardized feature matrix, and the regression coefficients, t-statistics, and two-tailed p-values for each variable were calculated using t-tests. Any parameter with $p \geq 0.05$ (statistically insignificant under multivariate control) was considered to have its explanatory power for wind speed overshadowed by other variables and was therefore excluded from the final feature set. The advantage of this method lies in using "variable contribution within a linear framework" as the screening criterion. By eliminating linearly redundant variables before proceeding to complex nonlinear models, it reduces dimensional noise in subsequent modeling and ensures the feature set possesses clearer physical interpretability. The model is fitted using maximum likelihood estimation and implemented using the 'Ordered Model' class from the 'statsmodels' library in Python.

5.3.2 Screening Results

The model performs OLS multiple linear regression on the 10 standardized candidate features based on $n = 7,161$ observation points. The standardized regression coefficients (β), t-statistics, and significance results for each variable are as follows:

Table 5-5 Results of Regression Analysis for Urban Morphology Parameters

Parameter (Optimal Scale)	Standardized Coefficient β	t-value	p-value	Conclusion
C_150 (Open Space Coverage)	+0.413	+4.752	p=0.000	Significant
D_150 (Building Density)	-1.291	-5.705	p=0.000	Significant
FAI_75 (Frontal Area Index)	-0.344	-5.506	p=0.000	Significant
FAR_30 (Floor Area Ratio)	-1.431	-24.256	p=0.000	Significant
Hm_30 (Average Building Height)	+0.661	+13.571	p=0.000	Significant
HV_30m (Variation in building height)	+0.354	+9.300	p=0.000	Significant
S_50 (Open Space Meandering)	-0.240	-7.879	p=0.000	Significant
SVF150 (Sky View Factor)	-0.098	-1.913	p=0.056	Borderline, excluded
W_150 (Open Space Width)	+0.288	+1.475	p=0.140	Not significant, excluded
λb_{30} (Building Floor Area Density)	-0.121	-2.700	p=0.007	Significant

5.3.3 Interpretation of Results

Based on the results of the multiple linear regression analysis, the eight urban morphological parameters ultimately retained have a statistically significant impact on pedestrian wind speed. The direction of their regression coefficients aligns closely with physical mechanisms and can be classified into two categories based on their effects: inhibitory and exacerbating.

Suppressive factors refer to urban form elements where an increase in parameter values leads to a decrease in pedestrian wind speed and an improvement in pedestrian level wind environment levels. Among the eight parameters screened in this study, five belong to the

suppressive category. Floor Area Ratio (FAR₃₀) is the factor with the strongest influence, with a standardized regression coefficient of -1.431 and an absolute t-statistic value of 24.3, making it the most significant factor in the multivariate model. This parameter reflects the total volume of buildings within a plot; a higher floor area ratio indicates a stronger overall blocking effect of the building complex on incoming airflow, creating an effective wind shadow zone on the leeward side of the buildings, thereby significantly reducing pedestrian-level wind speed. Building density (D₁₅₀) also exhibits a strong mitigating effect, with a regression coefficient of -1.291. At a 150-meter scale, this parameter characterizes the density of building coverage in the surrounding area; higher density results in stronger overall obstruction of the background wind field, thereby substantially reducing the risk of pedestrians being exposed to strong winds. The regression coefficient for the windward area index of the podium (FAI₇₅) is -0.344. At a medium scale of 75 meters, this parameter comprehensively reflects the dual blocking effects of both the near-field and background fields, and its mitigating effect is consistent with the results of the univariate analysis. The regression coefficient for Open Space Sinuosity (S₅₀) is -0.240. This parameter characterizes the degree of curvature in the street network; the higher the sinuosity, the weaker the ability of airflow to penetrate in a straight line through open spaces, and the more effectively wind energy is dissipated at the ground level. The regression coefficient for building coverage (λb_{30}) is -0.121. An increase in local building density enhances surface roughness, effectively shielding near-surface airflow.

Aggravating factors refer to morphological elements where an increase in parameter values leads to higher pedestrian wind speeds and a lower pedestrian level wind environment rating. The screening results identified three parameters exhibiting aggravating characteristics. Average building height (Hm₃₀) is the risk factor with the greatest impact, with a regression coefficient of +0.661. Increased building height triggers the canyon effect and downwash effect, whereby high-rise buildings transport the momentum carried by strong upper-level winds downward to pedestrian height, resulting in a significant increase in near-surface wind speeds. The regression coefficient for the coefficient of variation in building height (HV_{30m})

is +0.354. This parameter characterizes the degree of irregular variation in building height; the more pronounced the height variations, the greater the turbulence and gust intensity at the building interface, making it easier for complex local acceleration zones to form. The regression coefficient for open space coverage (C_{150}) is +0.413. This parameter characterizes the sparsity of the building layout; a higher proportion of open space means less obstruction of airflow by buildings, allowing wind to travel unimpeded along the corridor, reflecting a typical wind corridor effect.

The sky visibility factor (SVF_{150}) and open space width (W_{150}) lost their independent significance under multivariate control and were therefore excluded. Specifically, the explanatory power of the sky visibility factor was absorbed by the building density parameter, as the two exhibit strong multicollinearity in reflecting the degree of spatial openness; meanwhile, the influence of open space width was no longer independently significant after controlling for the other eight variables. It is worth noting that building floor area coverage (λb_{30}) emerged as significant in this round of analysis. This is related to adjustments in the optimal calculation scale: when the wind-facing area index of the podium was adjusted from 30 meters to 75 meters and the open space coverage from 50 meters to 150 meters, the collinearity structure among the parameters changed, allowing the independent contribution of building floor area coverage to become apparent. Based on the above screening results, the next chapter will focus on these eight key morphological parameters to further derive and propose urban morphological optimization guidelines aimed at enhancing pedestrian level wind environment.

5.4 Development of a Pedestrian level wind environment Prediction Model Based on Random Forest and XGBoost Ensemble Learning Algorithms

5.4.1 Analytical Methods and Model Validation Strategies

To further validate the conclusions of ordered logistic regression and capture the potential nonlinear relationship between urban morphological parameters and wind speed categories, this study introduces the XGBoost (eXtreme Gradient Boosting) ensemble

learning algorithm, using Random Forest as a benchmark for comparison. By iteratively constructing a sequence of decision trees and minimizing the regularization loss function, XGBoost can automatically capture interaction effects and nonlinear patterns among features; Random Forest, on the other hand, achieves good robustness and stability by aggregating the results of multiple independent decision trees through ensemble voting.

Unlike traditional regression analysis, which uses R^2 to measure goodness of fit, the evaluation of a classification model's generalization ability requires eliminating the “memory effect” of the predictive model on existing data. This study adopts k-fold cross-validation (k-Fold CV) as the core validation strategy, specifically setting $k=5$ (5-fold). k-fold cross-validation randomly divides the entire dataset into k mutually exclusive subsets (folds). In each iteration, $k-1$ of these subsets are used as the training set to fit the model, while the remaining subset serves as the test set to evaluate performance; this process is repeated k times, ensuring that each subset is used exactly once as a test set. In this study, SMOTE oversampling was applied to the minority "high-risk" samples (204 samples, accounting for 2.8%) to address the issue of class imbalance. To strictly prevent data leakage, the SMOTE operation was encapsulated within the Python ImbPipeline pipeline and executed only on the training set of each fold; the test set always retained its original true distribution, ensuring the unbiasedness of the CV evaluation results. This study included a total of **$n = 7,161$** measurement points. After 5-fold splitting, approximately 1,432 measurement points were allocated to each test set, while 5,713 measurement points were used as the training set. The specific process is shown in the table:

Table 5-6 Five-fold Cross-Validation Process

Training Iteration	Training Set (Number of Data Points)	Test Set (Number of Data Points)	SMOTE Scope
Fold 1	Fold 2–5 (≈ 5729)	Fold 1 (≈ 1432)	Only within the training set
Fold 2	Fold 1, 3–5 (≈ 5729)	Fold 2 (≈ 1432)	Only within the training set
Fold 3	Fold 1–2, 4–5 (≈ 5729)	Fold 3 (≈ 1432)	Only within the training set
Fold 4	Folds 1–3, 5 (≈ 5729)	Fold 4 (≈ 1432)	Only within the training set
Fold 5	Folds 1–4 (≈ 5729)	Fold 5 ($\approx 1,432$)	Within the training set only

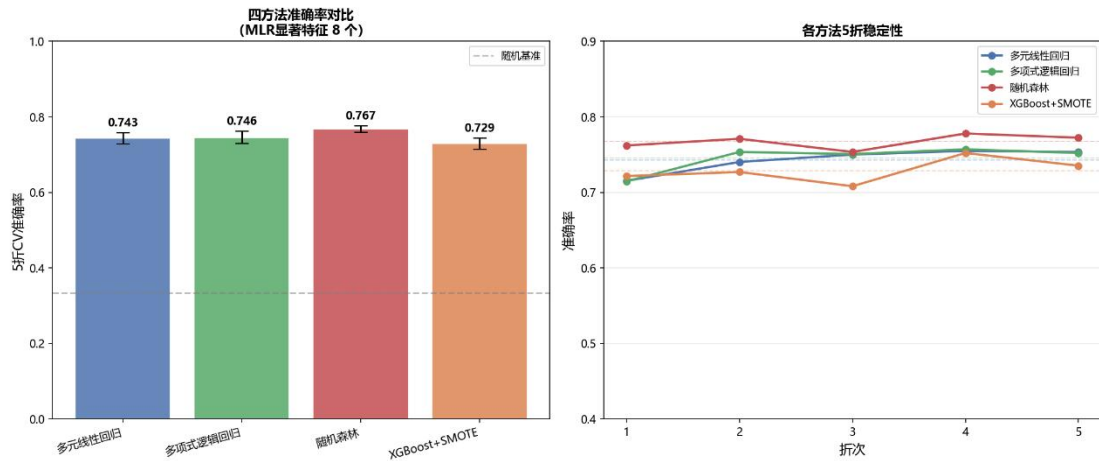


Figure 5-1 Comparison of training results for mainstream predictive models (Figure by author.)

During training, this model was also compared with other mainstream statistical prediction models, such as multiple linear regression. The final results showed that the random forest achieved a mean test accuracy of 0.767 ± 0.009 , with the smallest standard deviation (± 0.009). This small standard deviation indicates that the model performs consistently across different data subsets, making the conclusions robust and reliable. The final deployed model was refitted using the full dataset of 7,161 samples to maximize the model's learning of the complete feature distribution.

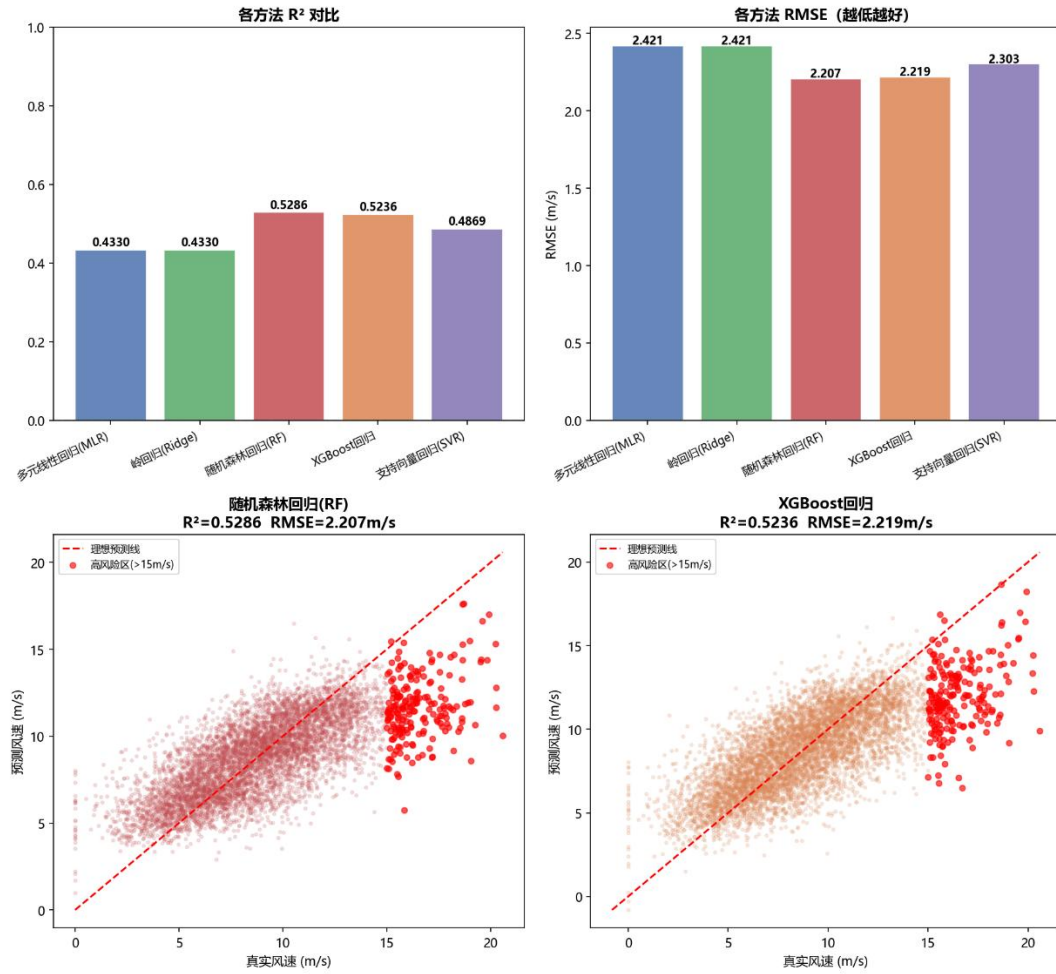


Figure 5-2 Wind speed prediction results and error analysis for mainstream prediction models (Figure by author.)

Finally, this study also attempted to predict specific wind speed values using different methods and constructed a wind speed prediction model based on urban morphological parameters. However, it was found that the predictive capabilities of various methods were not ideal; even the best-performing model achieved only $R^2 = 0.5288$ and $RMSE = 2.207$ m/s, indicating significant deviation. After careful analysis and plotting scatter plots, it was found that the greatest error lies in the poor predictive capability of the various models for extremely high wind speeds above 15 m/s, with a systematic underestimation. Further investigation revealed that there were only 204 observation points in the sample located in extremely high-risk areas with wind speeds above 15 m/s. This sample size was severely insufficient to support the predictive model's learning and identification of such high-wind-speed regions.

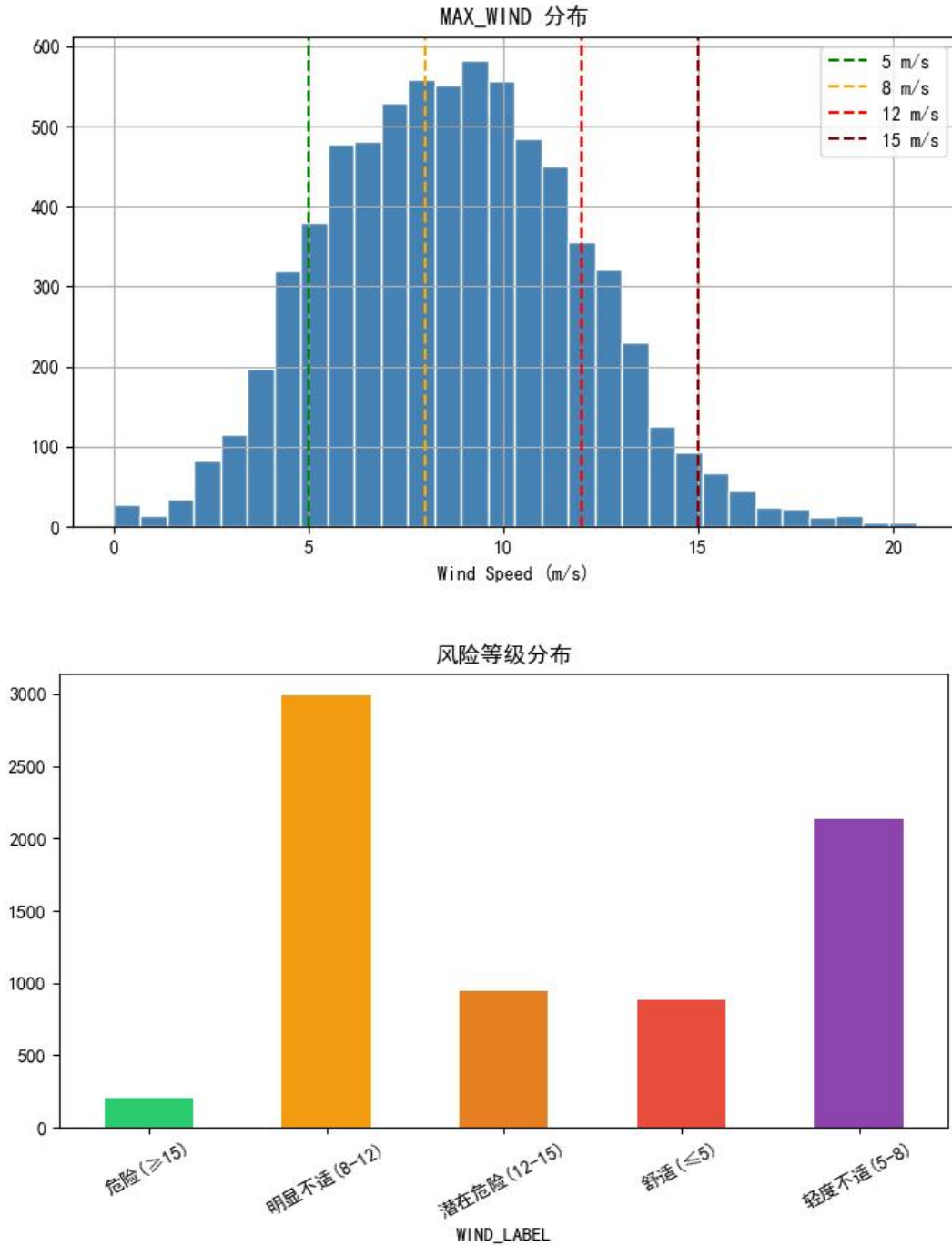


Figure 5-3 Statistical Analysis of Prediction Model Training Samples (Figure by author.)

5.5 Summary of This Chapter

This chapter established a comprehensive analytical framework—ranging from univariate screening and scale effect analysis to multivariate regression modeling and machine learning prediction—centered on the quantitative correlation mechanism between “urban morphological parameters” and “pedestrian level wind environment levels.” Through

in-depth analysis of empirical data from the Mong Kok district, the following key conclusions were drawn:

First, the urban morphological parameter system demonstrates strong explanatory power and widespread significance for pedestrian level wind environment. The study found that all 55 variables across the 11 selected morphological parameter categories at five observation scales exhibited highly significant correlations with pedestrian wind speed levels ($p < 0.001$). Among these, the Frontal Area Index (FAI) was confirmed as the core single factor influencing the wind environment in high-density districts. Spearman's correlation analysis indicated that FAI_30 is the optimal univariate predictor ($\rho = -0.565$). This suggests that the frontal blocking effect of building clusters on airflow is the primary physical mechanism for maintaining pedestrian level wind environment in high-density districts.

Second, the mechanisms by which morphological parameters influence the wind environment exhibit significant scale-dependent patterns. Experimental results reveal that parameters directly related to physical building obstruction (such as FAI, FAR, λb , and Hm) show the highest correlation at the small scale of 30 m; whereas parameters reflecting spatial openness and background exposure (such as D, SVF, and W) achieve optimal effects at the large scale of 150 m. This scale-dependent pattern provides a scientific basis for selecting appropriate scales in urban design practices when managing spatial dimensions.

Third, the multivariate regression model further clarified the nature of the effects and the synergistic relationships among the parameters. Under multivariate control conditions, 80% of the parameters still maintained a significant influence. Among them, D_{150} was the most potent inhibitory factor, while W_{150} acted as the primary intensifying factor. It is worth noting that the Sky View Factor (SVF) and building coverage ratio (λb) lost their independent significance in the model due to severe multicollinearity; their contributions to the wind environment were absorbed by building spacing (D) and the front-area index (FAI).

Fourth, this study ensured the robustness of its conclusions through algorithmic cross-validation and developed an efficient risk prediction tool. The feature importance rankings from the Random Forest algorithm and the results of ordered logistic regression

showed high consistency in identifying core factors, confirming the reliability of the evaluation system. Based on this, this chapter constructed a pedestrian level wind environment prediction model using the Random Forest algorithm; after five-fold cross-validation, its prediction accuracy for the three-level wind risk classification reached **76.7%**. This model can directly accept morphological parameters as inputs and rapidly output evaluation results, providing a practical technical pathway for high-density cities to conduct rapid pedestrian level wind environment risk screening during the scheme design phase without relying on complex CFD simulations.

Chapter 6 Proposal of Guidelines for Optimizing Urban Morphology for Pedestrian level wind environment and Examples of Morphological Remodeling

Urban form is the core physical factor influencing the wind environment at the pedestrian level. The patterns of parameter sensitivity revealed through numerical simulation and machine learning modeling not only hold explanatory significance at the academic level but should also be translated into actionable planning and design guidelines to guide pedestrian level wind environment planning practices in high-density urban areas. This chapter systematically constructs a multi-level urban form optimization strategy framework for pedestrian level wind environment, using the random forest classification model established in Chapter 5 as the core basis, and integrating standardized regression coefficients for various urban form parameters, optimal computational scales, and their physical significance.

The research framework of this chapter follows the logical sequence of "parameter sensitivity analysis → explanation of influence mechanisms → multi-scale design strategies → comprehensive guideline system," aiming to bridge quantitative modeling results with urban design practice and provide an evidence-based reference framework for pedestrian level wind environment planning in Hong Kong and similar high-density coastal cities.

6.1 Comprehensive Analysis of the Impact Mechanisms of Urban Form Parameters

6.1.1 Ranking of Parameter Influence Directions and Intensities

Based on Spearman correlation screening and OLS multiple regression significance tests in Chapter 5, eight urban form parameters were ultimately identified as having a statistically significant impact on maximum wind speed at the pedestrian level ($p < 0.05$). The standardized regression coefficients for each parameter are shown in Table 6-1.

Table 6-1 Summary of Standardized Regression Coefficients for Significant Urban Form Parameters

Parameter	Optimal Scale	Standardized Coefficient	Direction of Influence	Ranking of Influence Strength
Floor Area Ratio (FAR)	30 m	-1.431	Attenuation factor (wind speed reduction)	1
Building Density (D)	150 m	-1.291	Suppressive factor (reducing wind speed)	2
Average building height (Hm)	30 m	+0.661	Aggravating factor (increases wind speed)	3
Open Space Connectivity (C)	150 m	+0.413	Aggravating factor (increased wind speed)	4
Wind-Exposed Area Index (FAI)	75 m	-0.344	Attenuation factor (reduces wind speed)	5
Height Variation (HV)	30 m	+0.354	Aggravating factors (increased wind speed)	6
Building spacing (S)	50 m	-0.240	Attenuation factor (reduces wind speed)	7
Building coverage ratio (λ_b)	30 m	-0.121	Attenuation factor (wind speed reduction)	8

Note: The larger the absolute value of a standardized coefficient, the stronger the influence of that parameter on pedestrian wind speed. A positive coefficient indicates that wind speed tends to increase as the parameter increases, while a negative coefficient indicates the opposite.

Based on the direction of their influence, these parameters can be classified into two categories: wind speed-promoting parameters (Hm, C, HV) and wind speed-inhibiting parameters (FAR, D, FAI, S, λ_b). In urban design practice, the core logic of optimizing pedestrian level wind environment is as follows: in high-risk areas, reduce the values of wind speed-promoting parameters while appropriately increasing those of wind speed-inhibiting parameters; conversely, in areas requiring ventilation, apply the opposite approach to balance

the dual objectives of thermal comfort and pedestrian level wind environment.

6.1.2 The Spatial Hierarchical Significance of the Optimal Computational Scale

Another key finding of this study is that the influence of different urban morphological parameters peaks at different computational scales, a pattern that holds significant implications for planning hierarchies (Table 6-2).

Table 6-2 Optimal Computational Scales for Parameters and Corresponding Planning

Levels			
Optimal Scale	Relevant Parameters	Corresponding Planning and Design Level	Key Control Measures
30 m	FAR, Hm, HV, λb	Site and Building Design	Building Form, Podium Design, Building Height
50m	S	Block Group Design	Building Spacing Control, Street Cross-Sections
75 m	FAI	Block-scale design	Layout of building groups on the windward side
150 m	C, D	Master Plan for the District	Overall Density Pattern and Open Space System

The above results reveal that the formation of pedestrian wind speeds is a multi-scale, superimposed physical process: the density pattern at the district scale (150 m) establishes the baseline wind environment; the building cluster morphology at the block scale (75 m) determines local airflow obstruction and guidance; and building height and form at the plot scale (30 m) generate direct downwash and turbulence effects. This multi-scale nested characteristic indicates that design interventions at a single level are unlikely to effectively improve pedestrian level wind environment conditions; a coordinated response is required throughout the entire planning-design chain.

6.2 General Guidelines for the Design of High-Density Coastal Neighborhoods Based on Pedestrian level wind environment

6.2.1 Coordinated Control Strategies for Floor Area Ratio (FAR) and Building Density (D)

Floor Area Ratio (FAR; 30-meter scale, $\beta = -1.431$) and Building Density (150-meter scale, $\beta = -1.291$) are the two parameters with the strongest influence on pedestrian wind speeds in this study, both exhibiting a negative relationship; that is, urban forms with high FAR and high density help reduce wind speeds at the ground-level pedestrian layer. This conclusion is consistent with existing research on the "roughness effect" in high-density cities (Oke, 1987; Blocken et al., 2012): dense clusters of buildings collectively increase the resistance of the urban surface to airflow, causing near-surface wind speeds to decrease statistically.

However, it should be specifically noted that the aforementioned effects of floor area ratio and building density depend on the homogeneity of building distribution. In the case study area, both high-risk clusters A and B exhibit a coastal high-rise, medium-density pattern—where the floor area ratio is not low. However, precisely because this density is achieved through a small number of high-rise point towers rather than a homogeneous, medium-to-low-rise, high-density configuration, it generates strong “building corner flow” and “downwash” effects, leading to extreme wind speeds. It can thus be seen that simply pursuing a high floor area ratio does not necessarily ensure pedestrian level wind environment; the key lies in how the floor area ratio is achieved.

Design Strategy 1: Prioritize a "low-to-mid-rise, high coverage" development model

In areas with high pedestrian level wind environment risks (particularly on the windward side of the prevailing wind direction and in coastal zones), planning controls should prioritize encouraging a homogeneous development model featuring low-to-mid-rise buildings (8–15 stories), high building coverage ($\lambda_b > 0.35$), and high floor area ratios, as an alternative to a sparse, point-like high-rise layout. In the case study of this research, the probability of extremely high wind speeds occurring in the low-to-mid-rise dense building

area of Mong Kok (characterized by a homogeneous, high-coverage form) was significantly lower than in coastal areas with high-rise, medium-density development, providing empirical support for the aforementioned strategy.

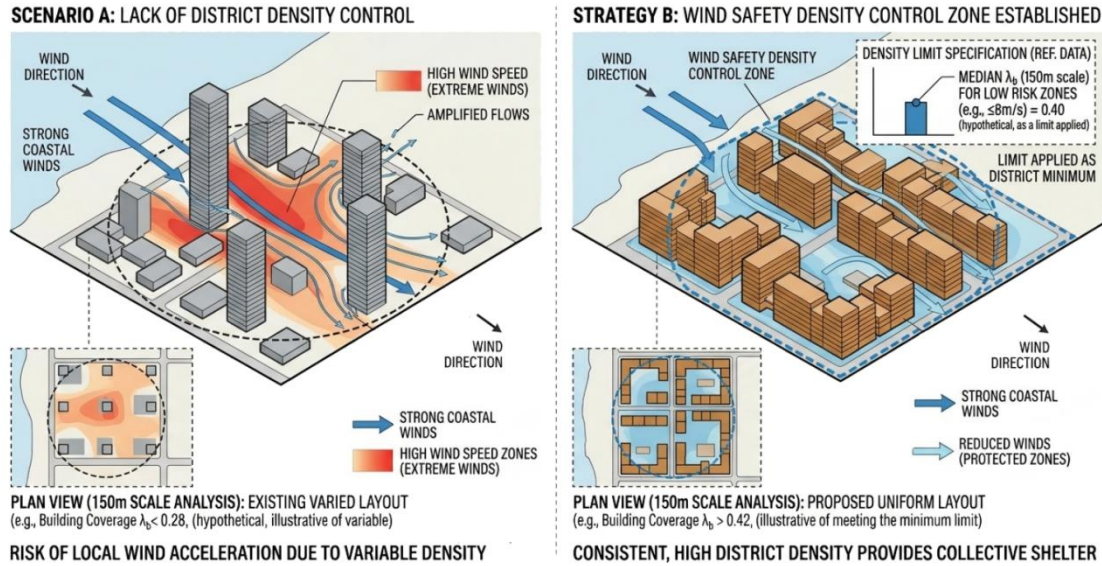


Figure 6-1 Schematic diagram of general urban form design strategies based on pedestrian level wind environment (Figure by author.)

Design Strategy 2: Establish Building Density Zoning Controls at the District Scale

Based on the finding that building density at the 150-meter scale has the greatest impact on wind speed, it is recommended that high-risk areas be designated as "pedestrian level wind environment density control zones" in statutory zoning regulations or urban design guidelines, with clear minimum building density thresholds established for a 150-meter radius within these zones. Specific indicators should be determined by referring to the wind speed statistics from the study's sample: the median building density at the 150-meter scale corresponding to low-risk zones ($\leq 8\text{ m/s}$) can serve as the reference lower limit for the control zones.

6.2.2 Zoning Height Control Strategies and Form Transition Strategies for Building Height

Average building height (30-meter scale, $\beta = +0.661$) is the most influential parameter among the wind-speed-promoting factors in this study, and its physical mechanism has been confirmed by numerous studies: high-rise buildings channel high-speed airflow from the upper atmospheric boundary layer to the pedestrian level through the "chimney effect" and "downwash effect," making them one of the primary sources of strong winds at the urban

pedestrian level (Davenport, 1972; Melbourne, 1978). Notably, the optimal calculation scale for this parameter is 30 m, indicating that the most direct influence stems from the local heights of individual buildings or a small number of adjacent buildings, rather than the average height over a large area. This provides a basis for refined plot-level control, suggesting that in high-risk coastal districts, architectural layouts with high-density ground-floor levels should be prioritized.

Design Strategy 3: Implement building height zoning controls in high-risk areas and establish mandatory requirements for podium structures

For plots identified as high-risk or potentially high-risk (based on high-risk probability heatmaps in this study), planning permit conditions should explicitly stipulate the following requirements: First, control the rate of height variation; building heights should gradually increase from the street boundary inward to avoid high-rise towers directly facing open spaces at pedestrian levels. On the windward side of the prevailing wind direction, towers should be set back from the street red line by no less than 10 meters, with the setback space filled by a podium (recommended podium height ≥ 15 meters, i.e., approximately 4–5 stories) to form a continuous street frontage. Second, regarding podium coverage requirements, the podium coverage ratio for street-facing plots is recommended to be no less than 60% of the plot area, to increase the building coverage ratio (λ_b) within a 30-meter scale and compensate for the downwash effect caused by high-rise towers. Finally, regarding height ratio control, within the same plot, the ratio of the main tower height to the podium height should not exceed 8:1, to avoid excessive impact on the ground-level wind environment caused by a single super-high-rise building.

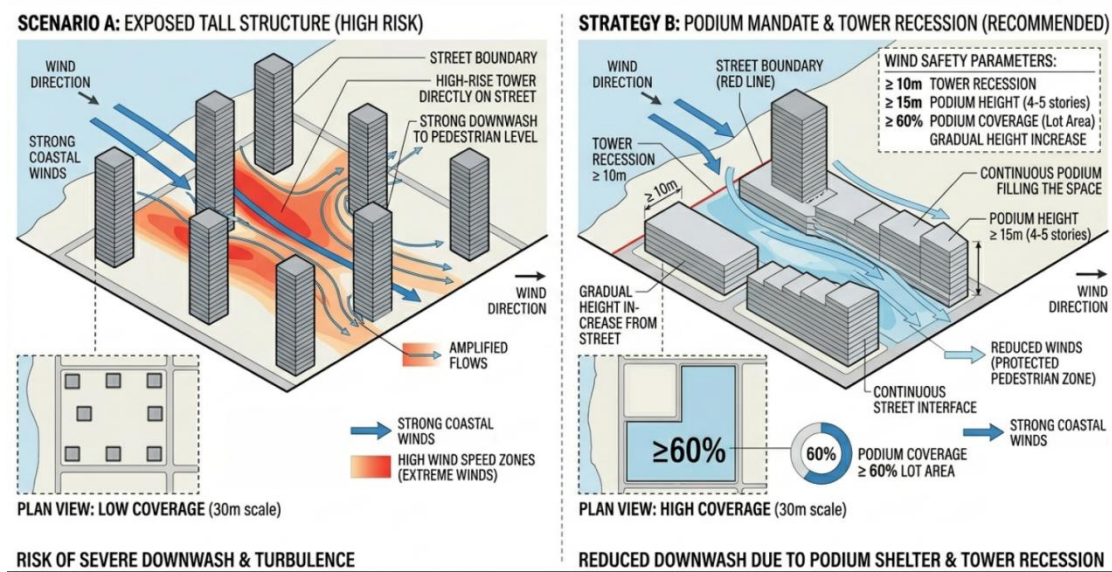


Figure 6-2 Schematic diagram of general urban form design strategies based on pedestrian level wind environment (Figure by author.)

The positive impact of building height variation (30-meter scale, $\beta = +0.354$) on pedestrian wind speeds stems from the phenomenon of airflow separation and reattachment at the interface between tall and short buildings: When airflow encounters a sudden change in building height, intense turbulence zones form on the roof and windward facade of the low-rise building, creating an accelerated wind zone in the open space between them (Lawson & Penwarden, 1975). This effect is particularly pronounced in typical urban renewal areas in Hong Kong where high-rise buildings adjoin low-rise, older structures.

Design Strategy 4: Establish Requirements for Building Height Transition Control

First, regarding adjacent height ratio restrictions, the building height ratio between adjacent plots (taller side/shorter side) should not exceed 3:1. When the height ratio exceeds this limit, a transitional volume (such as stepped setbacks or low-density ancillary structures) should be provided on the side of the shorter building, with a height of no less than 50% of the original building's height. Second, regarding morphological coordination in urban renewal zones, for redevelopment projects in old districts, new high-rise buildings must undergo a specialized assessment of their wind impact on surrounding existing low-rise buildings (referencing the requirements of the Hong Kong AVAS guidelines), and “not significantly exacerbating strong winds induced by changes in pedestrian-level height” should be

established as one of the conditions for planning approval. Finally, there is the control of the gradual change in the skyline. In the overall urban design layout, building heights should form a progressive, gradual increase from the city's interior toward the coastline, avoiding the isolated appearance of clusters of high-rise buildings that disrupt the sequence of height gradation.

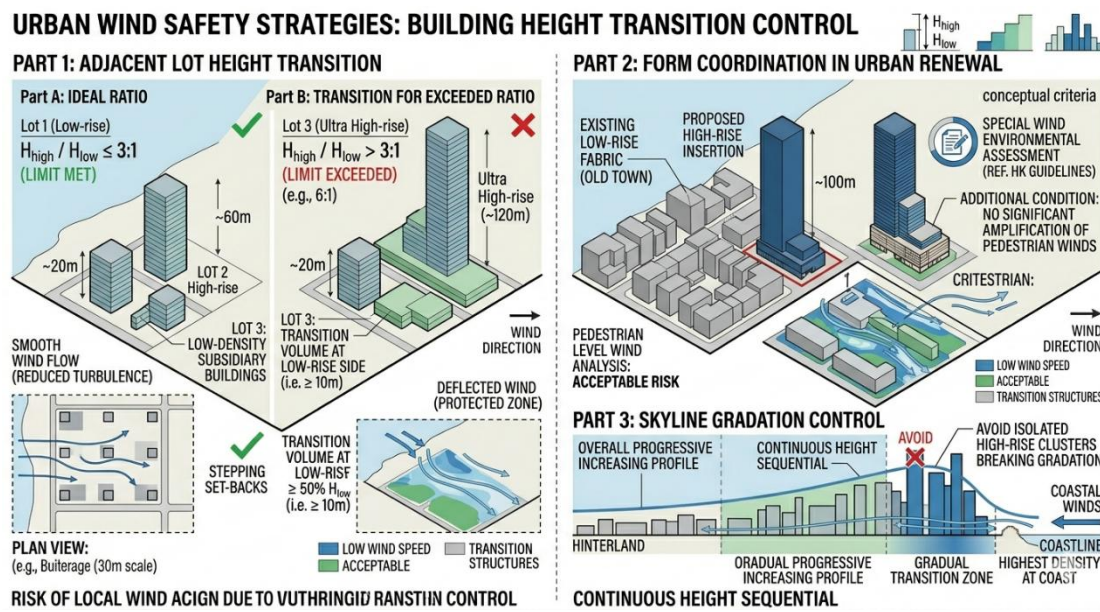


Figure 6-3 Schematic diagram of general urban form design strategies based on pedestrian level wind environment (Figure by author.)

6.2.3 Optimization Strategies for Wind Corridor Systems Based on Open Space Connectivity

The positive impact of open space connectivity (at a 150-meter scale, $\beta = +0.413$) on pedestrian wind speed reveals a paradox often overlooked in planning practice: while the quantity and quality of open spaces are undoubtedly important, when multiple open spaces form a continuous, unbroken chain along the prevailing wind direction, they create a "wind corridor acceleration effect" that significantly increases the wind speed experienced by pedestrians passing through them. This phenomenon is particularly evident in Hong Kong's coastal open public space system and aligns closely with the formation mechanism of extreme wind speeds in Cluster A (coastal high-rise, medium-density).

Design Strategy 5: Optimize the layout of the open space system and introduce “wind corridor regulation nodes”

Principle of staggered open space layout: Along the prevailing wind direction (primarily

the southeast monsoon in Hong Kong), adjacent open spaces should maintain appropriate staggered spacing or be separated by buildings to avoid forming continuous, unobstructed open corridors. It is recommended to establish building facades or dense greenery with a depth of no less than 30 meters between continuous open spaces to increase corridor resistance and reduce wind speeds.

Microclimate Design for Waterfront Public Spaces: For waterfront open spaces where layout changes are difficult, localized interventions through landscape design should be implemented in areas with higher wind speeds. These include: installing semi-permeable hedges or lattice enclosures with a ventilation rate of 40%–60% along the prevailing wind direction; planting evergreen trees to form windbreak belts (recommended planting density: ≥ 1 tree per linear meter, canopy coverage $\geq 70\%$); installing sunken activity platforms in the core areas of open plazas to utilize topographical elevation differences to reduce the actual wind speeds experienced by pedestrians.

Balancing Ventilation Corridors and Pedestrian level wind environment: Hong Kong's current Air Ventilation Assessment System (AVAS) framework emphasizes the protection and expansion of urban ventilation corridors, which creates tension with this study's goal of reducing pedestrian wind speeds in specific contexts. This study recommends introducing a principle of differentiated zoning controls in ventilation corridor planning: In densely populated inland areas where the urban heat island effect is pronounced, prioritize ensuring the continuity of ventilation corridors; whereas in areas where wind speeds are already high, such as the windward side of the coast, “deceleration nodes” should be incorporated into corridor design. This is achieved by appropriately increasing building screening within the corridor or planting tall trees to ensure that the upper limit of the “pedestrian activity” level (approximately 8 m/s) is maintained while guaranteeing basic air permeability.

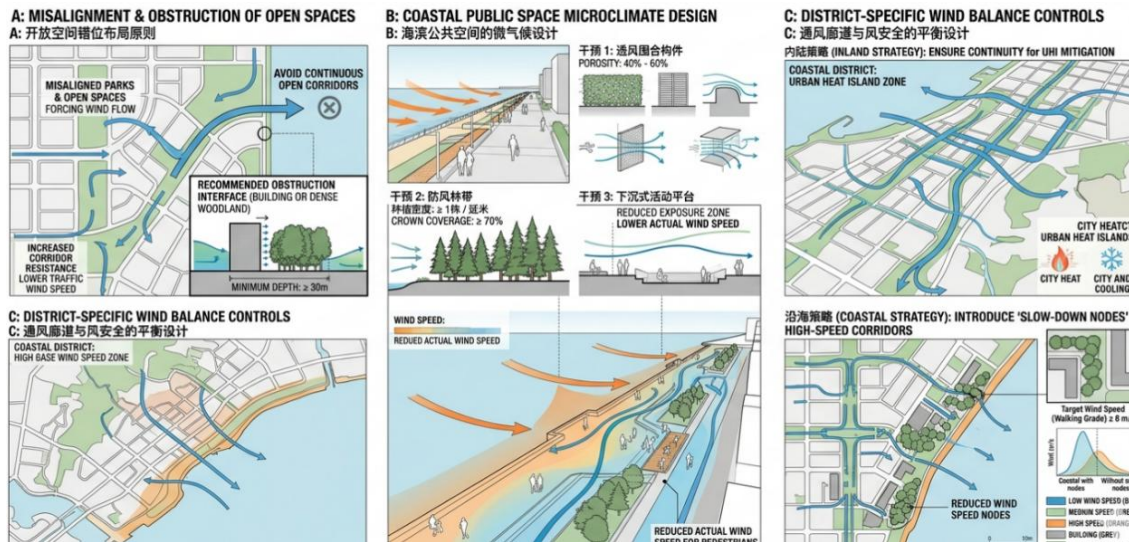


Figure 6-4 Schematic diagram of general urban form design strategies based on pedestrian level wind environment (Figure by author.)

6.2.4 Design Strategies for Podium Forms Based on the Podium Wind Exposure Area Index

The wind exposure area index (FAI, 75-meter scale, $\beta = -0.344$) calculated in this study is defined to account only for the windward projected area of building sections 15 meters or lower in height. Therefore, this parameter does not characterize the overall wind-blocking capacity of high-rise towers, but rather the direct shielding effect of podium volumes and low-rise building clusters at the street level on pedestrian-level airflow. This physical definition holds significant design implications: it demonstrates that, at the pedestrian scale, what truly determines whether incoming airflow can be effectively blocked is the density of the podium, ground-floor building mass, and street interface below 15 m—not the tower body towering above pedestrians' heads. The negative impact of FAI (≤ 15 m) ($\beta = -0.344$) indicates that within a 75-meter radius, the more continuous and dense the windward cross-section of a building below 15 meters, the lower the wind speed at the pedestrian level. This conclusion is highly consistent with findings in the field of wind engineering regarding “street canyon roughness”—when continuous, dense low-rise building facades exist on both sides of a street, airflow entering the street canyon slows significantly due to increased frictional resistance.

Design Strategy 6: Enhance the continuity of the podium and ground-floor building facades, replacing open ground spaces with dense, solid low-rise structures

In high-risk areas, podium design should prioritize “sealing” over “permeability.” It should not be guided solely by visual openness and commercial display, but rather ensure the solidity of the windward facade. It is recommended that the solid-to-void ratio (non-transparent, non-cantilevered sections) of the windward plinth facade be no less than 70%. The use of large-scale glass curtain walls or fully open ground floors should be restricted to increase the effective windward cross-sectional area below 15 meters in height. Regarding height limits, the effective upper limit for podiums is approximately 15 meters, corresponding to a building scale of 4 to 5 stories. It is recommended that the height of podiums on high-risk sites be controlled between 12 and 18 meters (approximately 3 to 5 stories). This effectively shields pedestrians from wind speeds at street level while serving as a transitional layer between the tower and the street, and should be used in conjunction with the height requirements for “podium soft landing” discussed later.

In addition to the main podium structure, arcades, walkways, and low-rise structures can also serve as effective supplementary wind-shielding interfaces. Traditional Hong Kong arcades, which form continuous solid side walls and roofs below 15 meters, constitute a natural high-FAI ($\leq 15\text{m}$) street interface. It is recommended that new projects along high-risk streets be encouraged to continue or add such systems to increase the low-rise wind-facing area within a 75-meter radius, while providing a pedestrian environment sheltered from wind and rain. For sites with limited podium coverage, the density of the street interface can be locally enhanced by installing green walls, solid perimeter walls, or low-rise structures ranging from 2 to 6 meters on the windward side, thereby further reducing peak wind speeds at the pedestrian level.

It should be noted that while increasing the windward area of the podium helps mitigate the direct impact of horizontal inflow on the pedestrian level, it cannot fully offset the downwash effect generated by high-rise towers. On sites with taller towers, the optimization strategy for FAI ($\leq 15\text{ m}$) should be used in conjunction with Strategy 3 (control of podium height and aspect ratio) to form a composite wind protection system where “lower levels block horizontal inflow and the top of the podium buffers downwash.”

many high-rise residential buildings in Hong Kong adopt this approach to enhance visual permeability and shared activity spaces, it can create localized wind tunnel effects in high-risk areas, negatively impacting wind speeds at pedestrian levels. Therefore, it is recommended that ground-floor cantilevers should not be fully open to the prevailing wind direction; partial enclosure or greenery should be incorporated on the windward side, while retaining lateral ventilation openings to maintain basic airflow. Furthermore, there is often a trade-off between high building coverage and high greening rates. This study recommends compensating for the loss of ground-level green space through vertical greening (roof gardens and vertical greenery) to maintain urban ecological functions while increasing building coverage, thereby achieving a synergistic enhancement of pedestrian level wind environment and ecological resilience.

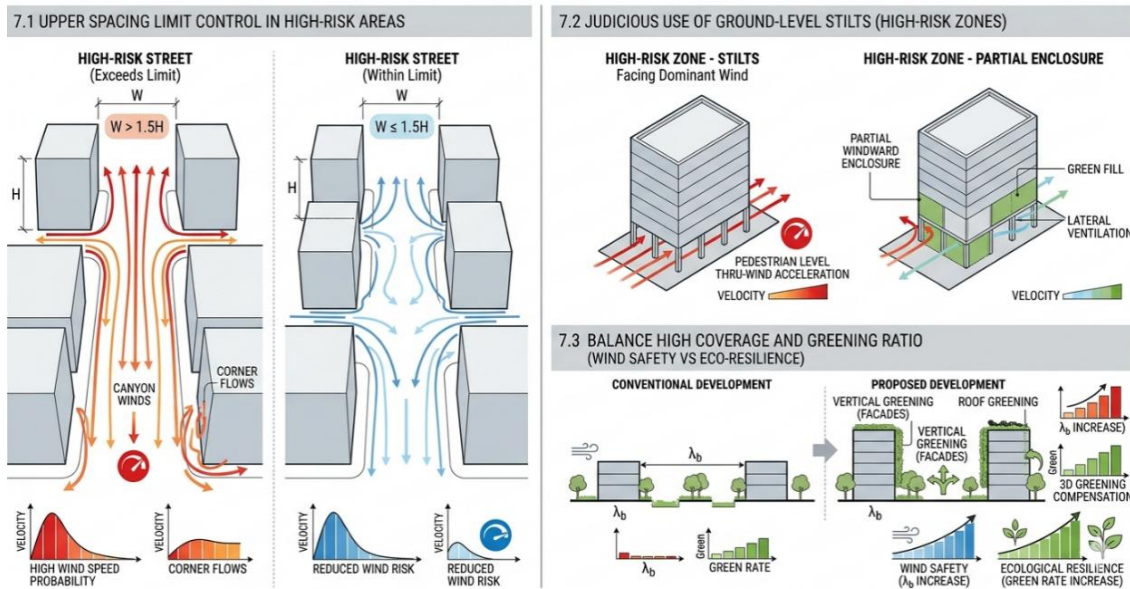


Figure 6-6 Schematic diagram of general design strategies for urban form based on pedestrian level wind environment (Figure by author.)

6.3 Comprehensive Guideline System and Zoning Applications

6.3.1 Risk-Based Zoning Control Framework

Integrating the pedestrian level wind environment risk assessment results from Chapter 4 with the parameter sensitivity analysis from Chapter 5, this study recommends dividing the study area into three control zones based on pedestrian level wind environment risk levels, each corresponding to design intervention requirements of varying intensity (Table 6-3).

Table 6-3 Framework for Urban Form Control Zoning Based on Risk Levels

Control Zone	Wind Speed Characteristics	Representative Areas	Control Intensity	Key Control Points
Category I Control Zone (High Risk)	Frequent high wind speeds >15 m/s	Coastal high-rise, medium-density residential areas A and B	Strict Control	Mandatory podium construction, height ratio restrictions, wind-blocking measures, and prohibition of full ground-floor cantilevers
Category II Control Zone (Moderate-Risk Area)	8–15 m/s, with possible local exceedances	Coastal Mid-Rise Transition Zone	Guidance-based Control	Recommended podium, gradual height variation, staggered layout of open spaces
Category III Control Zone (Low-Risk Maintenance Zone)	≤8 m/s, wind speeds generally manageable	Inland low-to-mid-rise dense areas such as Mong Kok	General Control	Maintain the existing high-density, homogeneous layout to prevent excessive high-rise development from disrupting the current favorable wind environment

6.3.2 Key Implementation Points at Each Planning and Design Level

At the master plan level, the core task of pedestrian level wind environment management is to establish an overall density zoning framework and the layout of the open space system. Specific measures include: designating high-risk areas as "Special Pedestrian level wind environment Control Zones" in statutory zoning plans, and clearly defining the maximum building height envelope and connectivity requirements for open spaces within these zones; Based on the influence patterns of building density parameters at the 150-meter scale, establish building density guidance indicators in coastal windward zones, prioritizing homogeneous, low-to-mid-rise high-density development while restricting isolated super-tall towers; coordinate the planning of urban ventilation corridors with pedestrian level wind environment controls, and introduce design requirements for deceleration nodes where

corridors traverse high-risk sections.

At the urban design level, the parameter sensitivity patterns revealed by this study should be translated into spatial design guidelines at the block level. Key operational points are as follows: Based on the influence of the FAI parameter at the 75-meter scale, introduce a "wind-shading efficiency assessment" phase into design review procedures, requiring applicants to submit a calculation explanation of the FAI index for building clusters facing the prevailing wind direction; Based on the influence patterns of the building height variation (HV) parameter, establish requirements for gradual changes in building height profiles within blocks; prohibit adjacent buildings with abrupt height changes, and specify formal requirements for transitional building volumes in the form of urban design guidelines; incorporate the maximum building spacing (rather than the usual minimum spacing) as an additional control indicator for high-risk sections into the design conditions notice.

At the architectural design level, the dominant influence of 30-meter-scale parameters (FAR, Hm, HV, λ_b) alerts designers that the form of a single building plot has a direct and significant impact on the pedestrian wind environment; design constraints should not be limited solely to meeting regulatory requirements such as sunlight access and fire safety. Specific operational recommendations are as follows: For new projects located in Class I control zones (high-risk zones), wind tunnel testing or CFD numerical simulation assessments should be commissioned during the architectural design phase, with compliance with pedestrian wind speed standards serving as a prerequisite for design approval; the use of streamlined floor plans or corner-trimming treatments in the design of high-rise towers is encouraged to reduce corner flow effects ;the design of continuous street-facing facades is advocated to avoid creating excessively large open spaces at the base of towers, thereby maintaining λ_b near the upper limit of the plot coverage requirement.

6.3.3 Limitations and Scope of the Guidelines

It should be noted that the design guideline system proposed in this study is based on the following assumptions, and its applicability limits should be considered during practical implementation:

First, while this study covers multiple wind direction scenarios, it remains limited by the

number of simulated conditions. This study used PALM-4U to perform numerical simulations for eight wind direction scenarios, fully accounting for the unstable nature of wind directions under strong convective weather conditions. Compared to studies that simulate only a single dominant wind direction, this approach offers greater coverage of operational conditions. However, the combinations of wind direction, wind speed, and atmospheric stability in actual atmospheric environments far exceed eight. The simulation results of this study represent the maximum wind speed envelopes at each monitoring point under limited conditions, rather than a complete statistical distribution of wind climate. Furthermore, this study did not consider extreme wind events such as direct typhoon landfalls; the distribution patterns of pedestrian wind speeds under such extreme conditions may differ from those under conventional conditions. It is recommended that future studies, when conditions permit, expand to finer wind direction resolutions (e.g., 16 or 24 directions) and assign frequency weights to each scenario based on local wind rose diagrams to obtain more statistically representative pedestrian level wind environment assessment results.

Second, the sample scope of this study is concentrated in high-density urban environments. The study area covers typical high-density urban districts from Mong Kok to the coastal areas of Hong Kong, where parameter ranges differ significantly from those in low-density suburban areas. When applying the guidelines from this study to medium- and low-density cities, the threshold ranges for each parameter should be adjusted to local conditions.

Third, the classification model still has limitations in identifying high-risk areas. The recall rate for the high-risk category in the final model of this study is 37.3%, meaning that approximately 62% of actual high-risk locations are misclassified by the model as medium-risk. Therefore, the "medium- and high-risk areas" identified by this model should be understood as reference areas with a higher probability of risk. In specific engineering decisions, verification should still be conducted in conjunction with on-site CFD simulations or wind tunnel tests.

6.4 Example of Morphological Optimization for High-Risk Old Neighborhoods in Hong Kong Based on Pedestrian level wind environment

6.4.1 Study Area Overview: Ma Tau Kok District

Ma Tau Kok is located on the eastern part of the Kowloon Peninsula and administratively belongs to Kowloon City District. Geographically, it borders Kowloon Bay to the east and faces the former Kai Tak Airport runway across the water. The "Five Streets" area (comprising Ming Lun Street, Chung Shun Street, Hing Yin Street, Hing Yan Street, and Ma Tau Kok Road), which is the focus of this study, is a typical, extremely high-density old neighborhood in Hong Kong. Most of the buildings in this area were constructed in the 1950s and 1960s and consist primarily of 5- to 8-story tenement buildings, with the ground floors densely occupied by small-scale industrial activities such as auto repair and metal fabrication.

In terms of urban fabric, the Ma Tau Kok area exhibits a highly regular and compact orthogonal grid structure. Street widths are generally narrow (approximately 4–8 meters), while building density is extremely high, creating deep and narrow urban street valleys. As the Urban Renewal Authority (URA) has designated this area as a core pilot site for the “neighborhood renewal” model, its statutory planning documents (such as the Ma Tau Kok Outline Zoning Plan S/K10/31) have explicitly permitted its redevelopment into high-density residential buildings reaching up to 120 meters above the main horizontal datum. This signifies that the area is undergoing a dramatic transition from “low-rise, high-coverage” to “high-rise, ultra-high-density” development, and the drastic changes in its three-dimensional form will have far-reaching implications for the local microclimate, particularly the wind environment for pedestrians at street level.

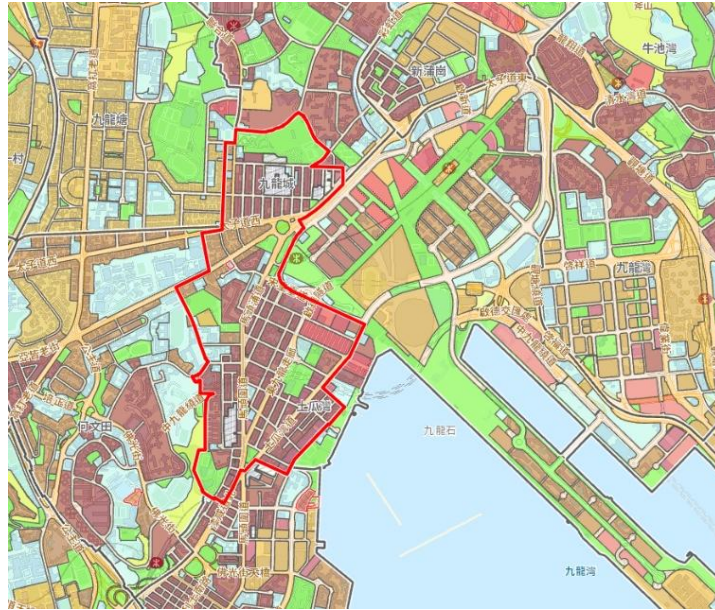


Figure 6-7 Site awaiting renewal in the Ma Tau Kok district, Kowloon, Hong Kong (Source: Hong Kong Statutory Planning Information System)

6.4.2 Regional Climate Characteristics and Wind Field Background

Hong Kong is located in a subtropical monsoon climate zone, and its wind environment is significantly influenced by both the monsoon climate and the complex topography of its coastline. Based on long-term observational data from the Hong Kong Observatory (HKO) and relevant meteorological stations, the prevailing wind directions in the region exhibit distinct seasonal variations throughout the year: the northeast monsoon dominates in winter, while southerly winds (i.e., southwest and southeast winds) prevail in spring and summer.

For the Ma Tau Kok coastal site, the southeasterly (SE) monsoon represents the wind environmental boundary condition of greatest research value and highest risk. The waters of Kowloon Bay provide a vast fetch for the southeasterly inflow; due to minimal frictional resistance over the sea surface, the airflow retains high kinetic energy and wind speed. When these undisturbed sea breezes reach the coastal interface at Ma Tau Kok, the abrupt transition from the rough sea surface to the dense urban landscape at the boundary triggers intense airflow turbulence. This specific climatic context makes Ma Tau Kok a typical “wind corridor outpost” for Hong Kong during spring and summer, serving as both a key entry point for urban ventilation and a potential risk area for wind-related safety incidents.

facades of these high-rises, the airflow, influenced by high-pressure zones, moves downward along the facades, creating intense downwash. Since the “Five Streets” site currently lacks sufficient buffer setbacks and podium barriers, this phenomenon of high-altitude energy reaching the ground directly will result in extremely high turbulence intensity and instantaneous gusts at the base of the podium. This morphological transition from 20-meter-tall tenement buildings to 120-meter-tall towers exposes the previously relatively sheltered pedestrian spaces to a complex high-altitude downwash flow field, creating a significant safety hazard.

Finally, there is the risk of corner vortices triggered by abrupt changes in the urban form. Under the “neighborhood redevelopment” model, the interior of the site may feature a mix of high-rise towers and remaining old buildings. As airflow passes around the corners of high-rise buildings, pressure differentials drive the formation of horizontal rotating vortices with extremely high flow velocities. In high-density neighborhoods like Ma Tau Kok, corner vortices often interact with street canyon winds, creating complex composite flow fields at building corners and intersections. This localized surge in wind speed not only degrades pedestrian comfort but also poses a direct threat to the safety of street-facing commercial facilities and vulnerable groups (such as the elderly and children) during wind disasters (e.g., typhoon season).

In summary, the coastal site in Ma Tau Kok is not only a key area for urban renewal in Hong Kong but also an extremely vulnerable zone sensitive to wind conditions. Under the dual pressures of “direct exposure to sea winds” and “ultra-high density,” how to mitigate inherent pedestrian level wind environment risks through scientific architectural form guidelines has become a core scientific issue that urgently needs to be addressed in the sustainable renewal of this area.



Figure 6-9 Example of urban form optimization based on pedestrian level wind environment for the study site

(Source: Hong Kong Statutory Planning Information System; redrawn by the author)

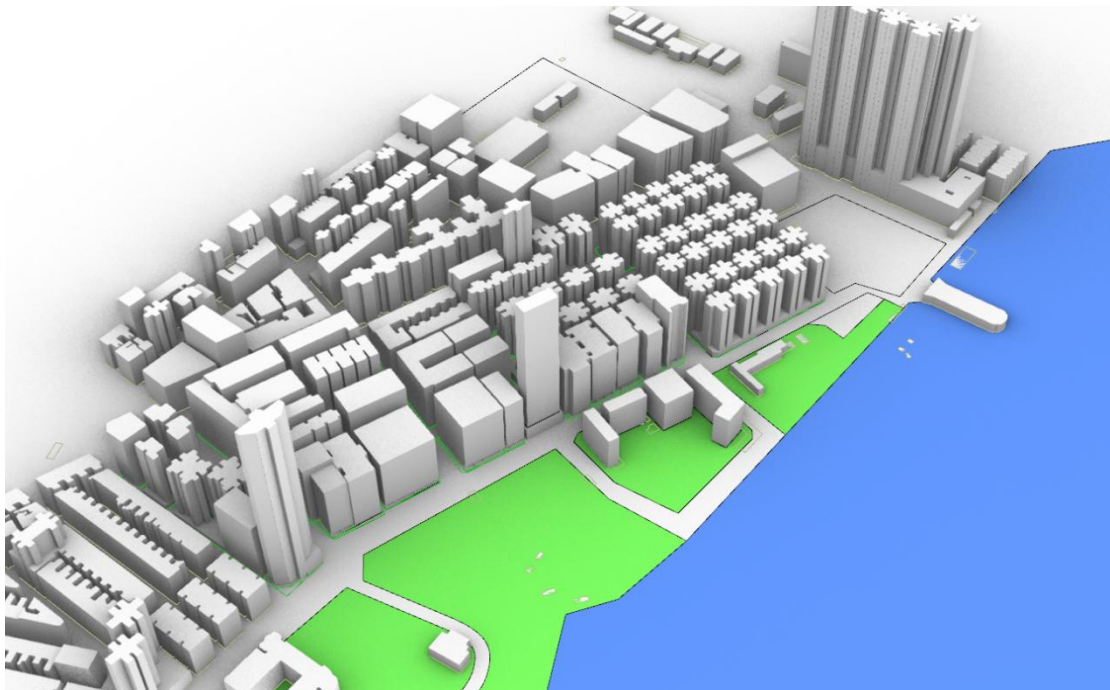


Figure 6-10 Current building form of the study site (Figure by author.)

6.4.4 Urban Renewal Design Approach for the Ma Tau Kok Coastal Area: Empirical Application of Pedestrian level wind environment Guidelines

For the “Five Streets” area in Ma Tau Kok—a typical high-risk coastal renewal site—this study proposes a form optimization scheme that balances the demands of high-density development with pedestrian level wind environment, based on the seven pedestrian level wind environment design guidelines established earlier. The core design logic begins with the reconstruction of the ground-level road network framework, extending to macro-level skyline regulation, meso-level block form reconstruction, and micro-level building facade treatment, thereby achieving a transition from “experiential design” to “parameter-driven design.”

6.4.5 Strategies for Reshaping the Spatial Framework and Redirecting the Road Network

In the morphological reconstruction of the “Five Streets” area in Ma Tau Kok, the primary challenge is addressing the structural flaw of the existing road network, which “faces the sea breeze head-on.” The current street alignment runs almost perpendicular to the coastline and is highly parallel to the dominant southeast (SE) wind direction in Hong Kong during spring and summer. This “zero-angle” layout allows strong sea breezes to penetrate unimpeded, creating a severe Venturi acceleration effect within the narrow street valleys. Based on the underlying logic of Design Strategies 7 and 5, this proposal geometrically deflects the original road network by approximately 30° to 45° eastward, aiming to alter the nature of the interaction between airflow and the urban surface at its source.

The physical significance of this road network deflection strategy lies in forcibly transforming the original “parallel sliding” airflow into a “diagonal collision” pattern. When the southeasterly sea breeze reaches the coastal interface, deprived of a direct energy discharge channel, the airflow first collides with the windward facade of the deflected buildings, creating a significant high-pressure stagnation zone at the building's leading edge. This forces the airflow to dissipate its kinetic energy and overflow into the upper atmosphere. This adjustment, without altering the overall building mass, effectively increases the effective wind-exposed area index at pedestrian height ($FAI \leq 15$ m), causing the sea breeze to undergo a preliminary cliff-like deceleration before entering the inland hinterland, thereby establishing

a low-speed flow field as a foundation for subsequent morphological optimization.

Furthermore, adjustments to the road network layout ensure the stability of the microclimate within the block. The reoriented streets no longer function as urban wind corridors but transform into mutually shielded “wind shadow pockets,” significantly increasing the resistance to airflow passing between the building clusters. Through this reconstruction of the geometric and topological dimensions, the design not only alleviates wind pressure along the coastal front but also significantly reduces the probability of extreme wind speeds within the site by increasing the sinuosity (S-parameter) of building spacing, thereby achieving a refined balance between urban ventilation needs and pedestrian level wind environment management.

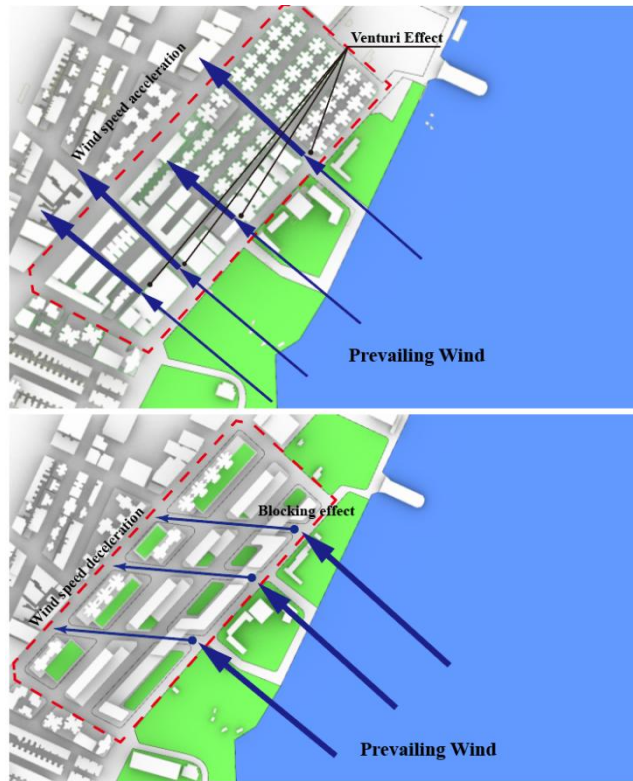


Figure 6-11 Impact of road network configuration adjustments on the pedestrian wind environment (Drawn by author.)

6.4.6 Gradual Skyline Transition and Coordinated Height Control at the Macro Level

After defining the ground-level road network framework, the macro-scale skyline configuration becomes the key to regulating the downwash of the atmospheric boundary layer. The Ma Tau Kok district is currently undergoing a dramatic transition from 20-meter-tall

low-rise buildings to 120-meter-tall high-rise residential buildings. If a traditional “uniform-height screen-like” layout were adopted, it would easily induce strong flow patterns on the seaward side. Based on Design Strategy 4, this proposal establishes a stepped skyline profile that gradually rises from the coastline toward the inland hinterland. This morphological gradient guides high-speed airflow at high altitudes to ascend upward rather than plunge directly toward pedestrian activity zones at ground level. In terms of specific morphological control parameters, the proposal strictly adheres to the constraint that the height ratio between adjacent buildings (taller side to shorter side) does not exceed 3:1. At the boundary between “5th Street” and the yet-to-be-renovated “13th Street” old district, the design introduces stepped transitional volumes. By incorporating ancillary structures or setbacks that are no less than 50% of the height of adjacent low-rise buildings, the design effectively mitigates the turbulent zones caused by abrupt changes in height. This height coordination strategy not only reduces the intensity of corner vortices but also prevents the new high-rise buildings from causing severe negative microclimatic impacts on the surrounding existing low-rise residential areas.

Furthermore, through refined zoning controls on the average building height (H_m), the proposal strategically positions the 120-meter high-rise towers toward the inland side, while prioritizing low-to-mid-rise development within the 50-meter coastal zone. This layout logic ensures that the downwash generated by the high-rise towers falls within the internal buffer zone of the site, rather than directly impacting the vulnerable coastal promenade. Through this three-dimensional height evolution, the proposal transforms what would otherwise be an isolated cluster of high-rise buildings into an urban ensemble with an overall roughness interception effect, thereby mitigating the penetration and transmission of high-altitude wind energy to the street level from a macro perspective.



Figure 6-12 Impact of building height control on the pedestrian wind environment

(Drawn by author.)

6.4.7 Block-Scale Podium Interventions and Interface Filling Mechanisms

To address the physical threat posed by downwash from high-rise buildings reaching the ground, this design prioritizes the core strategy of “mandatory podium requirements.” The proposal abandons the traditional practice of high-rise residential towers landing directly on the ground, opting instead for a “low-to-mid-rise, high coverage ratio ($\lambda_b > 0.6$)” podium model. Specifically, the proposal establishes a continuous, dense row of low-rise buildings ranging from 25 to 45 meters in height along the seaward interface, serving as the first physical barrier to intercept the airflow. Through this interception mechanism based on a continuous, dense interface, the downwash airflow is effectively converted into horizontal turbulence before reaching the ground, significantly reducing the destructive force of instantaneous gusts at the pedestrian level. At the micro-scale, the design adopts a counterintuitive “interface-filling” logic to optimize the wind-facing area index. In accordance with Strategy 6, the design requires that the solidity ratio of the windward facade of the first row of buildings facing the sea be no less than 70%. By reducing the proportion of ground-floor voids, the design artificially increases the surface roughness at the pedestrian scale. Simultaneously, the main tower is required to set back at least 10 meters from the podium boundary. This spatial buffer, combined with a continuous system of street arcades, significantly narrows the airflow inlets between buildings and blocks the acceleration paths of

localized through-drafts.

To address residual wind corridors that cannot be completely blocked by the building form, the design further introduces “dynamic obstruction nodes” for supplementary intervention. In the middle section of the primary ventilation pathways, a rooftop greening system is installed to further dissipate wind energy through the microscopic friction of the plant canopy. This composite defense system—comprising the physical interception by the podium and the energy dissipation by vegetation—ensures that pedestrian wind speeds within the street remain below safe thresholds even under extreme southeast monsoon conditions, providing a model for interface treatment in high-density urban renewal projects.

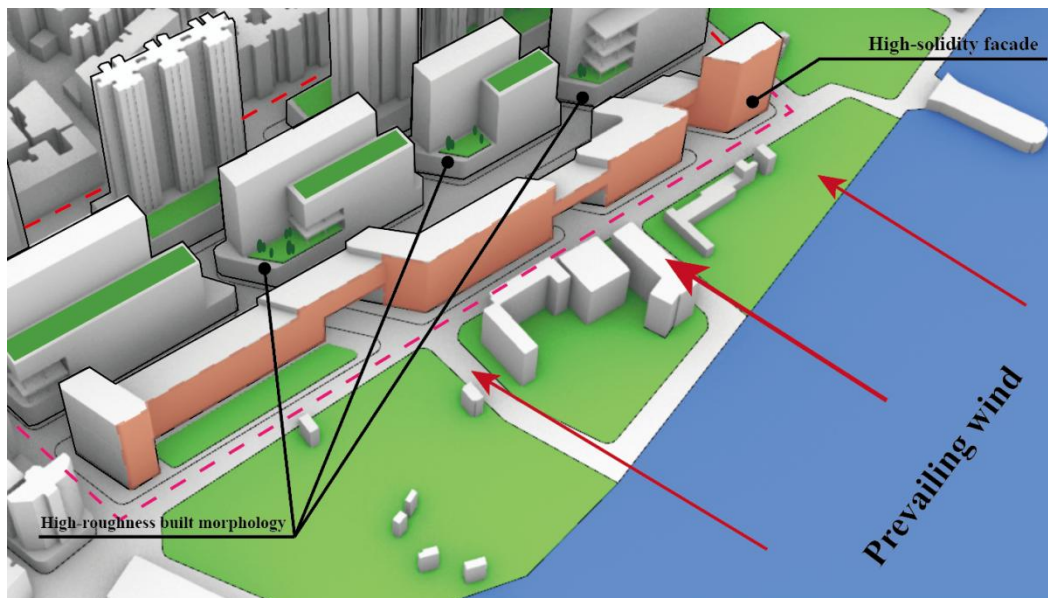


Figure 6-13: Impact of Form Control on Pedestrian Wind Environment (Drawn by author.)

6.4.8 Synergistic Compensation Between Enhanced Ecological Resilience and Form Control

Since the design significantly increased the building coverage ratio (λ_b) to ensure pedestrian level wind environment, this has to some extent reduced the permeable green space at ground level. To balance the tension between pedestrian level wind environment control and ecological sustainability, this study adopted a balanced strategy of “vertical compensation” and “functional integration.” In accordance with Strategy 7, the design transfers the lost ground-level green space to the rooftops of the continuous podium, establishing a large-scale green roof system covering the entire district. This not only achieves a scientifically sound compatibility between the site's floor area ratio and building density within statutory planning

requirements but also expands the city's ecological footprint in the vertical dimension.

From the perspective of microclimate optimization, rooftop greening not only provides aesthetic value but also significantly mitigates wind turbulence beneath the towers through the three-dimensional roughness created by the vegetation canopy. Through this design approach of “wind-resistant solidity at the base and open ecology at the top,” the Ma Tau Kok renewal plan ensures pedestrian safety while alleviating the heat island effect in high-density neighborhoods via the transpiration of rooftop vegetation. In summary, through precise, full-scale regulation of the road network orientation, skyline profile, podium form, and ecological interfaces, this plan has successfully transformed the Ma Tau Kok district from a vulnerable “wind disaster hotspot” into a high-quality urban space with wind environment resilience.

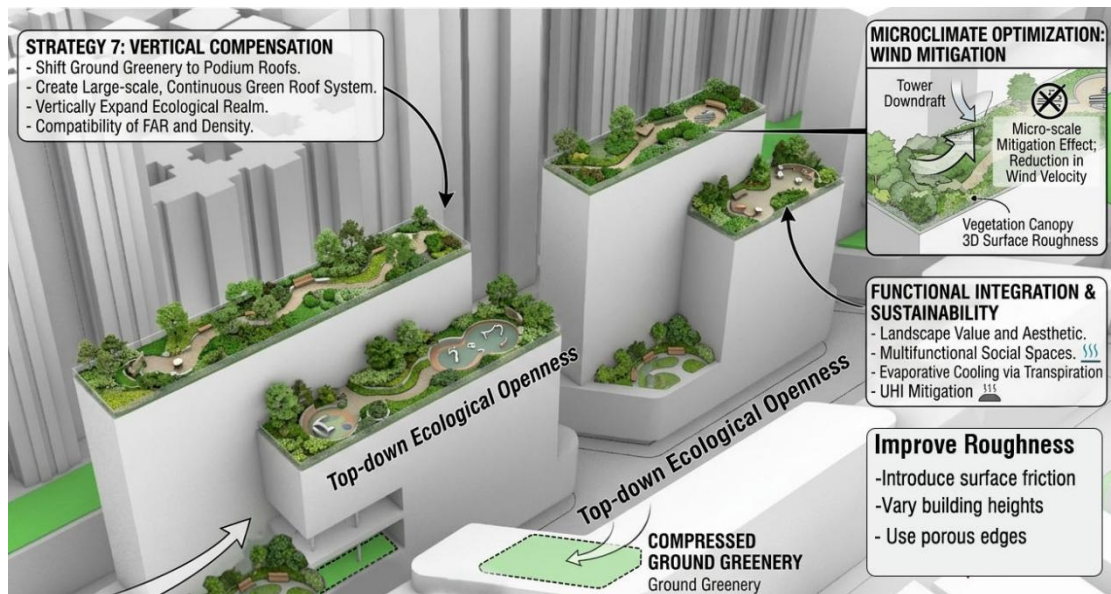


Figure 6-14 Optimization of the wind environment and urban ecological resilience through rooftop greening (Drawn by author.)

6.4.9 Site plan and conceptual rendering after architectural form optimization



Figure 6-15 Wind-Safety-Based Optimization of the Ma Tau Kok Coastal Block Form—
Master Plan (Figure by author.)



Figure 6-16 Wind-Safety-Based Optimization of the Ma Tau Kok Coastal Block Form—
Aerial View (Figure by author.)

6.5 Summary of this chapter

Building upon the random forest prediction model and the multivariate regression analysis of urban form parameters presented in Chapter 5, this chapter systematically establishes a multi-level urban form optimization strategy framework focused on pedestrian level wind environment. Following a logical sequence of “parameter sensitivity analysis → explanation of influence mechanisms → multi-scale design strategies → comprehensive guideline system,” this chapter bridges quantitative modeling results with urban design practice, providing empirical evidence for pedestrian level wind environment planning in high-density coastal cities.

At the level of parameter influence mechanisms, this chapter identifies eight urban form parameters that significantly affect pedestrian wind speeds and classifies them into two categories: wind-promoting and wind-suppressing. The optimal calculation scales for each parameter range from 30 m to 150 m, revealing the multi-scale nested characteristics of the pedestrian wind speed formation process and indicating that pedestrian level wind environment optimization requires a coordinated approach across the entire planning-to-design chain.

Based on these findings, this chapter proposes systematic design guidelines covering core strategies such as development model selection, mandatory requirements for podium structures, height transition control, wind corridor node regulation, densification of windward facades, and differentiated spacing controls, thereby establishing a comprehensive intervention system spanning from the macro to the micro level. Building on this foundation, this chapter constructs a risk-tiered zoning control framework, classifying the study area into three categories: high-risk, medium-risk (requiring attention), and low-risk (requiring maintenance). It also objectively identifies the limitations of the guideline system regarding simulated operating conditions, sample scope, and model accuracy.

Finally, using the Ma Tau Kok district in Hong Kong as a case study, this chapter verifies the effectiveness and feasibility of the guideline system in engineering practice through full-scale regulatory measures such as road network deflection, gradual skyline

changes, podium infill, and ecological compensation, providing a replicable model for pedestrian level wind environment renewal in high-density cities.

Conclusion

Main Research Conclusions

This study takes Mong Kok, a high-density coastal urban district in Hong Kong, as its empirical case to systematically investigate the influence mechanisms of urban morphological parameters on pedestrian-level wind environment (PLWE) and to construct a machine learning-based rapid assessment model and design guidelines. The research first selects and defines eleven key morphological parameters from three dimensions—building geometry, open space, and topography—including floor area ratio (FAR), frontal area index (FAI), and open-space axis density (D). Through a sensitivity analysis of 7,161 grid cells at five scales ranging from 30 m to 150 m, it was found that the response of urban morphological characteristics to the computational scale exhibits distinct heterogeneous patterns. The mean building height (Hm) and open-space width (W) demonstrate strong statistical stability across different scales, whereas the podium frontal area index (FAI) and floor area ratio (FAR) are highly scale-sensitive. This finding clarifies that in high-density environments, due to the dramatic spatial fluctuations between high-rise towers and low-rise podiums, precise matching of parameters to their optimal scales of influence is essential. This provides a critical scientific basis for parameter selection in the predictive models developed later.

In terms of numerical simulation and validation, this study employs the large-eddy simulation tool PALM-4U to achieve high-precision microclimate simulation of a complex urban area. By calibrating against benchmark data from wind tunnel experiments, the optimal parameter combination for smooth-wall roughness ($z_0 = 0.001$ m) and near-ground wind speed compensation was determined, yielding a correlation coefficient of 0.777 between simulated results and measured data. The full-domain simulation results reveal the statistical distribution characteristics of pedestrian wind speed in the Mong Kok core area, identifying coastal mid- to high-rise building clusters and the exits of long-distance ventilation corridors as high-wind-speed risk concentration areas. Further quantitative correlation analysis shows that each morphological parameter contributes clearly to pedestrian wind speed with highly significant correlations ($p < 0.001$). Building density (D) and floor area ratio (FAR) are

identified as core "wind speed suppression" factors, with their optimal explanatory scale at the large scale of 150 m. In contrast, mean building height is the primary "wind speed promotion" factor, exhibiting its highest correlation at the 30 m scale. This scale-nesting characteristic profoundly reveals the dual nature of the near-ground wind field: it is both disturbed by local building geometry and regulated by the large-scale background urban wind field.

To overcome the bottleneck of delayed feedback from conventional CFD simulations in early design stages, this study successfully constructed a rapid prediction model for pedestrian wind environment grades based on Random Forest and XGBoost algorithms. Using 5-fold cross-validation, the model achieved a classification prediction accuracy of 76.7% for the three-level risk grade, with a standard deviation of only ± 0.009 , demonstrating strong stability and generalization ability. In the empirical application phase, this study transformed the quantitative regularities extracted from the Mong Kok data into actionable optimization guidelines and applied them to the urban renewal design of the Ma Tau Kok area. In this process, the study used the developed rapid prediction model to perform real-time comparison of pedestrian wind risk distributions before and after design optimization. The analysis shows that through interventions such as road network deflection, skyline gradient control, and podium interface filling, the area of high-risk points predicted by the model significantly decreased. This closed-loop demonstration clearly illustrates the practical value of the rapid prediction model in the design decision-making stage: it allows architects, without the need for specialized numerical simulation expertise, to obtain quantitative feedback on the wind environment impact of design adjustments within seconds, thereby enabling a paradigm shift from "post-hoc evaluation" to "design-phase preventive optimization".

Main Innovations of the Thesis

The innovative significance of this study is mainly reflected in the following three aspects. First, at the theoretical level, a multi-dimensional indicator system of urban morphological parameters is constructed, and the statistical heterogeneity and scale sensitivity of these parameters across different computational scales are systematically revealed, providing a more refined spatial analysis benchmark for microclimate research in high-density cities. Second, at the technical level, a "physical simulation – data-driven" dual-mode framework

integrating PALM-4U and ensemble learning is established, enabling the transformation from complex physical field computation to efficient decision-making tools. This approach greatly improves assessment efficiency while maintaining prediction accuracy. Third, at the application level, a complete technical logic of "morphological parameter sensitivity analysis → mechanism interpretation of influence → rapid prediction model → design guideline validation" is formed, offering a standardized pathway from quantitative diagnosis to spatial control for enhancing the climate resilience of coastal high-density urban blocks.

Limitations and Future Research Directions

Although this study has achieved interim results in methodological development and empirical exploration, certain limitations remain due to computational resources, data acquisition difficulties, and the constraints of engineering practice cycles. First, regarding simulation conditions, the current flow field data cover only eight prevailing wind directions. The model's predictive capability for transient, unsteady turbulent risks induced by direct typhoon landfalls or extreme short-duration strong gusts still needs to be extended by incorporating unsteady condition data. Second, the sample data for the prediction model established in this study is highly concentrated in the extremely high-density Mong Kok area of Hong Kong, and the parameter value ranges and scale response patterns exhibit distinct regional characteristics. Therefore, the generalizability and transferability of the model to low-density urban forms or urban environments in different climatic zones need to be revised and improved through multi-case cross-validation across more dimensions.

This study finds that the Random Forest model has certain limitations in handling imbalanced data, particularly achieving a recall rate of only 37.3% for high-risk areas (>15 m/s), posing a non-negligible risk of misclassification. This reflects the weakness of conventional machine learning algorithms in capturing the characteristics of extremely scarce extreme samples. Future research will focus on exploring methods to enhance the sensitivity of extreme wind speed identification, attempting to introduce multi-task learning frameworks or generative adversarial networks (GANs) to enhance the feature representation of minority class samples. In this way, without increasing the burden of physical simulation, the prediction bias caused by class imbalance can be addressed at the algorithmic level,

improving the model's early warning accuracy for extreme wind hazards.

Regarding the completeness of the parameter system, the current morphological indicators mainly focus on the geometric characteristics of building entities and open spaces, with insufficient coverage of “soft” elements in the urban underlying surface. In real environments, roadside vegetation, urban green spaces, and micro-topographies (e.g., slopes, sunken plazas) significantly affect the near-ground wind field through frictional dissipation and flow redistribution. Future research plans to incorporate key environmental parameters such as “vegetation canopy leaf area density” and “topographic upwind slope index” into the assessment framework, constructing a multi-dimensional morphological coupling model covering “building – space – vegetation – topography” in order to more realistically reproduce the combined influence of complex underlying surface conditions on pedestrian-level wind fields in high-density cities.

Finally, the optimized design for the Ma Tau Kok area in this study remains at the conceptual scheme stage, focusing on illustrating the logic of guideline implementation. Because urban renewal projects involve multi-stakeholder coordination and have long implementation and construction cycles, the current empirical process has not yet included long-term field observation data of wind environments after redevelopment, nor a subsequent post-occupancy large-eddy simulation evaluation. How to integrate this rapid prediction tool with refined life-cycle management of cities, especially using subsequent field measurement data to calibrate the model's prediction biases, will be a core direction of future research. Future work will aim to explore the nonlinear dynamic response mechanisms between morphological parameters and wind environment indicators, and to build an intelligent urban wind risk assessment and control system with higher resolution, multi-scenario coordination, and dynamic feedback capabilities.

References

- [1] AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2008, 96(10-11): 1749-1761.
- [2] BLOCKEN B, CARMELIET J. Pedestrian Wind Environment around Buildings: Literature Review and Practical Examples[J/OL]. *Journal of Thermal Envelope and Building Science*, 2004[2026-01-28].
<https://journals.sagepub.com/doi/abs/10.1177/1097196304044396>.
- [3] STATHOPOULOS T. Pedestrian level winds and outdoor human comfort[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2006, 94(11): 769-780.
- [4] Cooperative project for CFD prediction of pedestrian wind environment in the Architectural Institute of Japan - ScienceDirect[EB/OL]. [2026-01-28].
<https://www.sciencedirect.com/science/article/pii/S0167610507000645>.
- [5] TOPARLAR Y, BLOCKEN B, MAIHEU B, 等. A review on the CFD analysis of urban microclimate[J]. *Renewable and Sustainable Energy Reviews*, 2017, 80: 1613-1640.
- [6] MENG Y, HIBI K. Turbulent measurements of the flow field around a high-rise building[J]. *Wind Engineers, JAWE*, 1998, 1998(76): 55-64.
- [7] OKE T R. Street design and urban canopy layer climate[J]. *Energy and Buildings*, 1988, 11(1): 103-113.
- [8] BLOCKEN B, STATHOPOULOS T, CARMELIET J. CFD simulation of the atmospheric boundary layer: wall function problems[J]. *Atmospheric Environment*, 2007, 41(2): 238-252.
- [9] NG E, YUAN C, CHEN L, 等. Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong[J]. *Landscape and Urban Planning*, 2011, 101(1): 59-74.
- [10] YUAN C, NG E. Practical application of CFD on environmentally sensitive architectural design at high density cities: A case study in Hong Kong[J]. *Urban Climate*, 2014, 8: 57-77.
- [11] STATHOPOULOS T, BASKARAN B A. Computer simulation of wind environmental

- conditions around buildings[J]. *Engineering Structures*, 1996, 18(11): 876-885.
- [12]GRIMMOND C S B, OKE T R. Aerodynamic Properties of Urban Areas Derived from Analysis of Surface Form[J]. *Journal of Applied Meteorology*, 1999, 38(9): 1262-1292.
- [13]HUI Y, TAMURA Y, YANG Q. Analysis of interference effects on torsional moment between two high-rise buildings based on pressure and flow field measurement[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2017, 164: 54-68.
- [14]GROMKE C, RUCK B. Influence of trees on the dispersion of pollutants in an urban street canyon—Experimental investigation of the flow and concentration field[J]. *Atmospheric Environment*, 2007, 41(16): 3287-3302.
- [15]HEISLER G M, DEWALLE D R. 2. Effects of windbreak structure on wind flow[J]. *Agriculture, Ecosystems & Environment*, 1988, 22-23: 41-69.
- [16]WANG H, TAKLE E S. A numerical simulation of boundary-layer flows near shelterbelts[J]. *Boundary-Layer Meteorology*, 1995, 75(1): 141-173.
- [17]MOONEN P, GROMKE C, DORER V. Performance assessment of Large Eddy Simulation (LES) for modeling dispersion in an urban street canyon with tree planting[J]. *Atmospheric Environment*, 2013, 75: 66-76.
- [18]JACKSON P S, HUNT J C R. Turbulent wind flow over a low hill[J]. *Quarterly Journal of the Royal Meteorological Society*, 1975, 101(430): 929-955.
- [19]MILLER S T K, KEIM B D, TALBOT R W, 等. Sea breeze: Structure, forecasting, and impacts[J]. *Reviews of Geophysics*, 2003, 41(3): 2003RG000124.
- [20]BOTTEMA M. Urban roughness modelling in relation to pollutant dispersion[J]. *Atmospheric Environment*, 1997, 31(18): 3059-3075.
- [21]REN C, NG E Y, KATZSCHNER L. Urban climatic map studies: a review[J]. *International Journal of Climatology*, 2011, 31(15): 2213-2233.
- [22]NG E, YUAN C, CHEN L, 等. Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong[J]. *Landscape and Urban Planning*, 2011, 101(1): 59-74.
- [23]BLOCKEN B. Computational Fluid Dynamics for urban physics: Importance, scales,

- p possibilities, limitations and ten tips and tricks towards accurate and reliable simulations[J]. Building and Environment, 2015, 91: 219-245.
- [24] RATTI C, BAKER N, STEEMERS K. Energy consumption and urban texture[J]. Energy and Buildings, 2005, 37(7): 762-776.
- [25] CHENG V, NG E, CHAN C, 等. Outdoor thermal comfort study in a sub-tropical climate: a longitudinal study based in Hong Kong[J]. International Journal of Biometeorology, 2012, 56(1): 43-56.
- [26] YUAN C, NG E. Building porosity for better urban ventilation in high-density cities – A computational parametric study[J]. Building and Environment, 2012, 50: 176-189.
- [27] BLOCKEN B, STATHOPOULOS T, CARMELIET J. CFD simulation of the atmospheric boundary layer: wall function problems[J]. Atmospheric Environment, 2007, 41(2): 238-252.
- [28] REN C, NG E Y, KATZSCHNER L. Urban climatic map studies: a review[J]. International Journal of Climatology, 2011, 31(15): 2213-2233.
- [29] HE B J, ZHAO D X, ZHU J, 等. Promoting and implementing urban sustainability in China: An integration of sustainable initiatives at different urban scales[J]. Habitat International, 2018, 82: 83-93.
- [30] WONG N H, CHEN Y. Tropical Urban Heat Islands[M/OL]. 0 版 . Routledge, 2008[2026-01-29]. <https://www.taylorfrancis.com/books/9781134221103>.
- [31] LIU J, HEIDARINEJAD M, GRACIK S, 等. The impact of exterior surface convective heat transfer coefficients on the building energy consumption in urban neighborhoods with different plan area densities[J]. Energy and Buildings, 2015, 86: 449-463.
- [32] GIL J, MONTENEGRO N C, BEIRÃO J, 等. On the Discovery of Urban Typologies: Data Mining the Multi-dimensional Character of Neighbourhoods[C/OL]//eCAADe 2009: Computation: The New Realm of Architectural Design. Istanbul, Turkey, 2009: 269-278[2026-01-29]. http://papers.cumincad.org/cgi-bin/works/paper/ecaade2009_148.
- [33] RODE P, FLOATER G, THOMOPOULOS N, 等. Accessibility in Cities: Transport and Urban Form[M/OL]//MEYER G, SHAHEEN S. Disrupting Mobility. Cham: Springer International Publishing, 2017: 239-273[2026-01-29].

http://link.springer.com/10.1007/978-3-319-51602-8_15.

- [34]BLOCKEN B, CARMELIET J. Pedestrian Wind Environment around Buildings: Literature Review and Practical Examples[J]. *Journal of Thermal Envelope and Building Science*, 2004, 28(2): 107-159.
- [35]MELBOURNE W H. Criteria for environmental wind conditions[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 1978, 3(2): 241-249.
- [36]NEN W C. Wind danger in the built environment[J]. *Netherlands Standardization Institute, Delft*, 2006.
- [37]BLOCKEN B, STATHOPOULOS T, VAN BEECK J P A J. Pedestrian-level wind conditions around buildings: Review of wind-tunnel and CFD techniques and their accuracy for wind comfort assessment[J]. *Building and Environment*, 2016, 100: 50-81.
- [38]LO K W, CHAN P W, LAI K K, 等. Case studies of the winds in the urban area of Hong Kong – Microclimate station observations and high resolution numerical simulations[J]. *Heliyon*, 2024, 10(18): e37865.
- [39]ORWIG K D, SCHROEDER J L. Full-Scale Strong Winds from a Time-Varying Perspective[J].
- [40]VICKERY P J, TWISDALE L A. Wind-Field and Filling Models for Hurricane Wind-Speed Predictions[J]. *Journal of Structural Engineering*, 1995, 121(11): 1700-1709.
- [41]MENG Y, MATSUI M, HIBI K. An analytical model for simulation of the wind field in a typhoon boundary layer[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 1995, 56(2-3): 291-310.
- [42]LIU H, LIU X, NIE L, 等. Research Progress of Urban Wind and Thermal Environment Based on CiteSpace and China National Knowledge Infrastructure Database[J]. *Sustainability*, 2022, 14(20): 13108.
- [43]ZHONG J, LIU J, ZHAO Y, 等. Recent advances in modeling turbulent wind flow at pedestrian-level in the built environment[J]. *Architectural Intelligence*, 2022, 1(1): 5.
- [44]TAKEMI T, YOSHIDA T, HORIGUCHI M, 等. Large-Eddy-simulation analysis of airflows and strong wind hazards in urban areas[J]. *Urban Climate*, 2020, 32: 100625.

- [45] A fine-resolution ventilation performance spatial model at pedestrian-level based on wind tunnel studies for high-density neighborhoods[J]. *Building and Environment*, 2025, 281: 113207.
- [46] CHEN C, TIAN G, QIN S, 等. Generalization of Urban Wind Environment Using Fourier Neural Operator Across Different Wind Directions and Cities[EB/OL]. arXiv, 2025[2025-09-06]. <http://arxiv.org/abs/2501.05499>.
- [47] Urban ventilation assessment with improved vertical wind profile in high-density cities – Comparisons between LiDAR and conventional methods[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2022, 228: 105116.
- [48] HERSBACH H, BELL B, BERRISFORD P, 等. The ERA5 global reanalysis[J]. *Quarterly Journal of the Royal Meteorological Society*, 2020, 146(730): 1999-2049.
- [49] 刘勇洪;张硕;程鹏飞;陈鹏;魏来;房小怡. 面向城市规划的热环境与风环境评估研究与应用——以济南中心城为例[J]. *生态环境学报*, 2017(11 vo 26): 1892-1903.
- [50] 史源;任超;吴恩融. 基于室外风环境与热舒适度的城市设计改进策略——以北京西单商业街为例[J]. *城市规划学刊*, 2012(05 vo): 92-98.
- [51] 郭尚霖;孙一民. 广州地区街道微气候模拟及改善策略研究[J]. *城市规划学刊*, 2016(01 vo): 56-62.
- [52] 张雅妮;曾小洲;肖毅强. 基于风热环境优化的“山·城共构”城市设计初探——以广州白云新城为例[J]. *城市规划*, 2018(12 vo 42): 116-124.
- [53] 张云路;李雄. 基于城市绿地系统空间布局优化的城市通风廊道规划探索——以晋中市为例[J]. *城市发展研究*, 2017(05 vo 24): 35-41.
- [54] 林涛;殷实;余彬;何越阳;肖毅强;李香凝. 城市街区尺度风环境快速预测方法综述研究[J]. *建筑科学*, 2025(02 vo 41): 9-15.
- [55] 张清泉方兴华. 支撑钢框架结构抗风安全度与舒适度对比分析[J]. *华南理工大学学报(自然科学版)*, 1998(07): 120-123.
- [56] 罗紫元;曾坚. 城市化品质、城市韧性与“台风-暴雨”灾害风险分析——以 7 个东南沿海省市为例[J]. *科技导报*, 2021(15 vo 39): 124-134.
- [57] 欧进萍段忠东. 中国东南沿海重点城市台风危险性分析[J]. *自然灾害学报*, 2002(04):

9-17.

[58] YANG D, ZHANG N, TANG J. Impacts of urban morphology on typhoon-induced wind hazards at the pedestrian level[J]. *Urban Climate*, 2025, 60: 102351.

[59] Urban morphology detection and computation for urban climate research[J]. *Landscape and Urban Planning*, 2017, 167: 212-224.

[60] 申冲;沈傲;田春艳;魏晓琳;李磊;王明洁;陈训来;樊琦. 城市形态参数对边界层气象条件影响的模拟[J]. *中国环境科学*, 2019(01 vo 39): 72-82.

[61] 林智超. 室外风环境性能导向下的建筑立面形体开口布局寻优方法研究[J]. 2023(03).

[62] Wind tunnel tests on the relationship between building density and pedestrian-level wind velocity: Development of guidelines for realizing acceptable wind environment in residential neighborhoods[J]. *Building and Environment*, 2008, 43(10): 1699-1708.

[63] Superblock transformation in Seoul Megacity: Effects of block densification on urban ventilation patterns[J]. *Landscape and Urban Planning*, 2022, 222: 104401.

[64] Impact of morphological parameters on urban ventilation in compact cities: The case of the Tuscolano-Don Bosco district in Rome[J]. *Science of The Total Environment*, 2022, 807: 150490.

[65] Influence of urban geometry on outdoor thermal comfort in a hot dry climate: A study in Fez, Morocco[J]. *Building and Environment*, 2006, 41(10): 1326-1338.

[66] Calculation of wind in a Tokyo urban area with a mesoscale model including a multi-layer urban canopy model[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2008, 96(10-11): 1655-1666.

[67] CFD simulation of outdoor ventilation of generic urban configurations with different urban densities and equal and unequal street widths[J]. *Building and Environment*, 2015, 92: 152-166.

[68] The effect of building height and façade area ratio on pedestrian wind comfort of London[J]. *Journal of Wind Engineering and Industrial Aerodynamics*, 2019, 191: 63-75.

[69] The impacts of building height variations and building packing densities on flow

adjustment and city breathability in idealized urban models[J]. Building and Environment, 2017, 118: 344-361.

[70]Effect of uneven building layout on air flow and pollutant dispersion in non-uniform street canyons[J]. Building and Environment, 2011, 46(12): 2657-2665.

[71]Age of air and air exchange efficiency in high-rise urban areas and its link to pollutant dilution[J]. Atmospheric Environment, 2011, 45(31): 5572-5585.

[72]A framework for pedestrian-level wind conditions improvement in urban areas: CFD simulation and optimization[J]. Building and Environment, 2020, 184: 107191.

[73]The effect of building height diversity on outdoor microclimate conditions in hot climate. A case study of Dubai-UAE[J]. Urban Climate, 2020, 32: 100611.

[74]The breathability of compact cities[J]. Urban Climate, 2015, 13: 73-93.

[75]An Investigation of the Quantitative Correlation between Urban Spatial Morphology Indicators and Block Wind Environment[EB/OL]. [2025-09-07].
<https://www.mdpi.com/2073-4433/12/2/234>.

[76]A New method of simulating urban ventilation corridors using circuit theory - ScienceDirect[EB/OL]. [2025-09-07].
<https://www.sciencedirect.com/science/article/pii/S2210670720301499>.

[77]Sky view factor measurement by using a spherical camera[EB/OL]. [2025-09-07].
https://www.jstage.jst.go.jp/article/agrmet/75/2/75_D-18-00027/_article/-char/ja/.

[78]Numerical Studies on the Influence of Building Morphology on Urban Canopy Wind Speed - Sun - 2024 - Journal of Advances in Modeling Earth Systems - Wiley Online Library[EB/OL]. [2025-09-07].
<https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2023MS003881>.

[79]Pedestrian level wind around super-tall building: Effects of podium - IOPscience[EB/OL]. [2025-09-07]. <https://iopscience.iop.org/article/10.1088/1755-1315/218/1/012036/meta>.

[80]Wind tunnel study of pedestrian level wind environment around tall buildings: Effects of building dimensions, separation and podium[J]. Building and Environment, 2012, 49: 167-181.

- [81]On the influence of roof shape on flow and dispersion in an urban street canyon[J]. Journal of Wind Engineering and Industrial Aerodynamics, 2013, 123: 107-120.
- [82]Effects of non-uniform and orthogonal breezeway networks on pedestrian ventilation in Singapore's high-density urban environments[J]. Urban Climate, 2018, 24: 460-484.
- [83]Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong[J]. Landscape and Urban Planning, 2011, 101(1): 59-74.
- [84]Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: A study in Hong Kong[J]. Landscape and Urban Planning, 2011, 101(1): 59-74.
- [85]LI B, LIU J, LI M. Wind tunnel study on the morphological parameterization of building non-uniformity[J]. Journal of Wind Engineering and Industrial Aerodynamics, 2013, 121: 60-69.
- [86]JI H, LI Y, LI J, 等. A Novel Quantitative Approach to the Spatial Configuration of Urban Streets Based on Local Wind Environment[J]. Land, 2023, 12(12): 2102.
- [87]Impact of natural urban terrain on the pedestrian wind environment in neighborhoods: A CFD study with both wind and buoyancy-driven scenarios[J]. Building and Environment, 2024, 261: 111746.
- [88]LAWSON T, AD P. THE EFFECTS OF WIND ON PEOPLE IN THE VICINITY OF BUILDINGS.[J/OL]. 1977[2026-03-24]. <http://pascal-francis.inist.fr/vibad/index.php?action=getRecordDetail&idt=PASCAL7780305984>.
- [89]NG E. Feasibility study for establishment of air ventilation assessment system (AVAS)[J]. J. HKIP, 2007, 22(1): 39-45.

Appendix

Appendix1:Analysis of Urban Forms Parameter Characteristics

1) The distribution range of **C (open space coverage)** is between 0% and 100%, with a concentration around 60% – 80%. This indicates that open spaces dominate in the Wangjiao neighborhood, where the building density is approximately 29%. This parameter is insensitive to grid cell size, with the mean remaining stable (71 – 72%) across all scales, suggesting that the distribution characteristics of open spaces remain consistent across different observation scales.

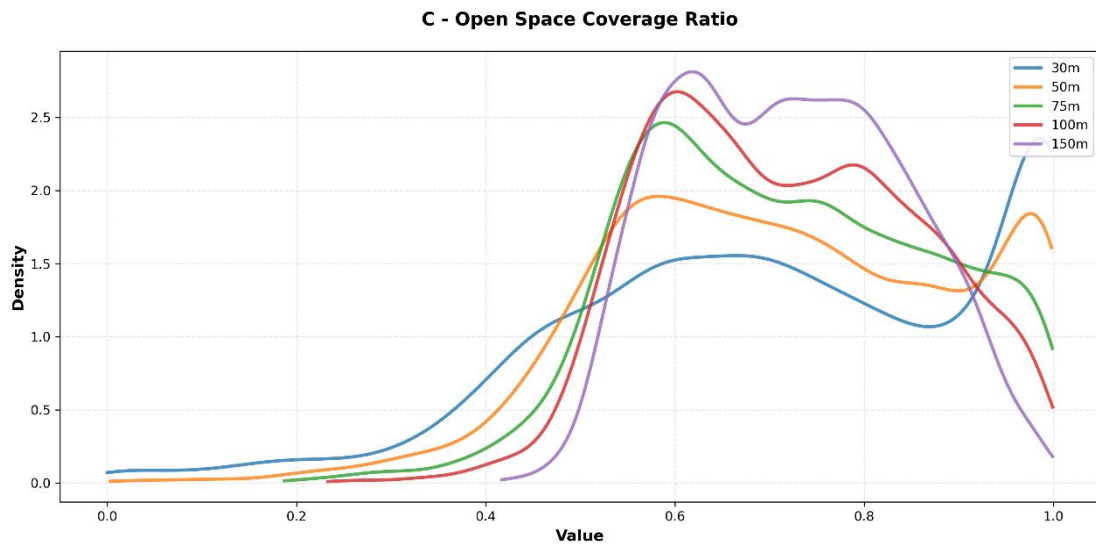


Figure 7-1 Statistical Distribution of Urban Morphology Parameter C (Figure by author.)

2) The distribution range of **Hm (average building height)** is wide, and the central tendency shifts upward as the grid size increases (approximately 21 m at 30 m grid size and approximately 25 m at 100 m grid size), indicating that the Mong Kok district is dominated by mid- to high-rise buildings. As the grid cell size increases, the parameter distribution converges toward the median; when the grid cell size reaches $\geq 100 \text{ m} \times 100 \text{ m}$, the distribution stabilizes (with a 21.7% increase), indicating that a $100 \text{ m} \times 100 \text{ m}$ scale is necessary to adequately reflect the average building height characteristics of the Mong Kok district.

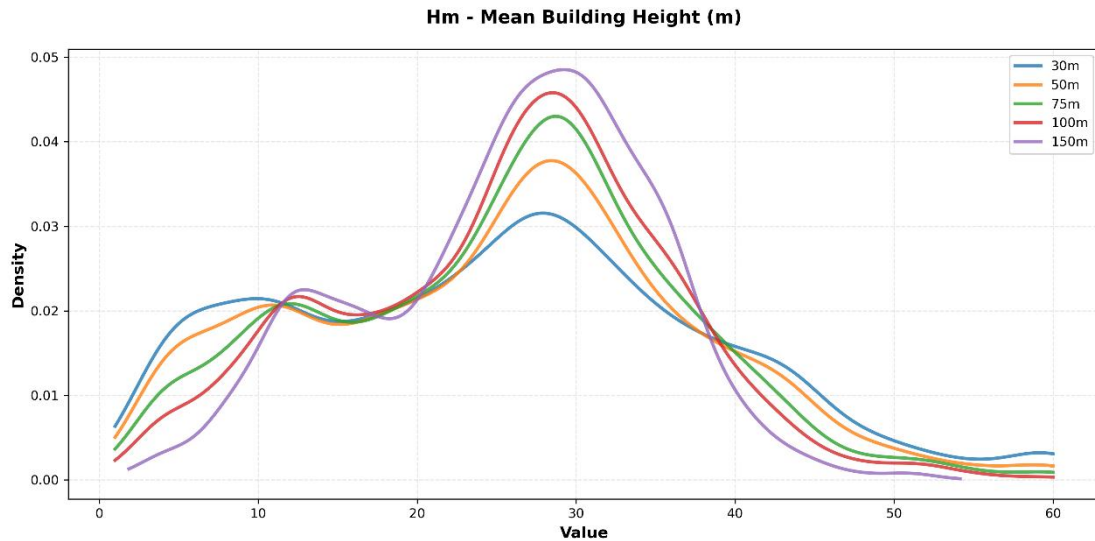


Figure 7-2 Statistical Distribution of Urban Form Parameter Hm (Figure by author.)

3) The distribution range of **HV (coefficient of variation for building height)** is relatively broad, concentrated between 6.4 m and 18.0 m, indicating that building heights in the Mong Kok district vary significantly and the skyline exhibits pronounced undulations. As the grid cell size increases, the mean of the parameter continues to rise (by 71.9%). The coefficient of variation in building height is highly sensitive to grid cell size, reflecting the capture of greater height variations within a larger observation area.

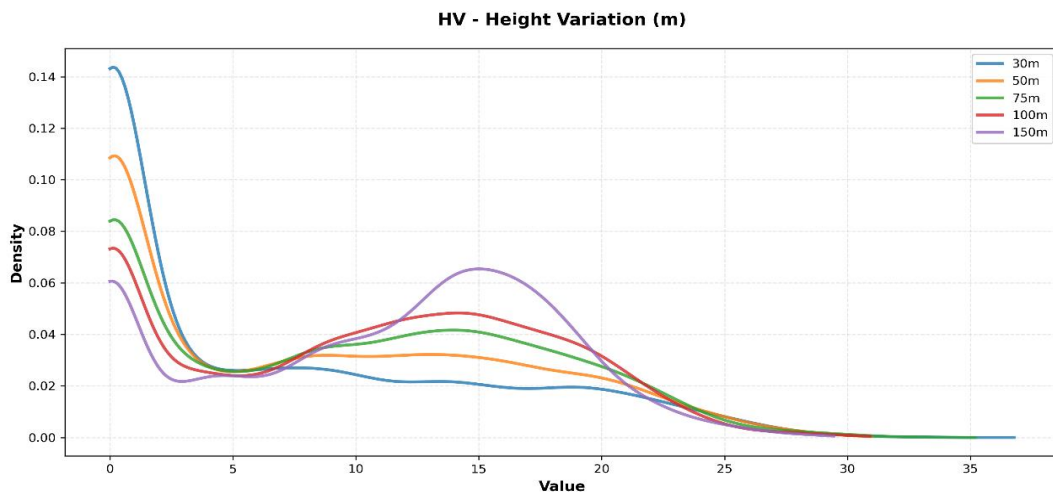


Figure 7-3 Statistical Distribution of Urban Form Parameter HV (Figure by author.)

4) The distribution range of **FAR (floor area ratio)** is relatively broad, with a concentration between 1 and 3, indicating that the development intensity in the Mong Kok district is moderate. When the grid cell size is $\geq 75 \text{ m} \times 75 \text{ m}$, the frequency distribution of the parameter tends to stabilize (fluctuating between 2.42 and 2.52), suggesting that a $75 \text{ m} \times 75$

m scale is necessary to adequately reflect the land development intensity characteristics of the Mong Kok district.

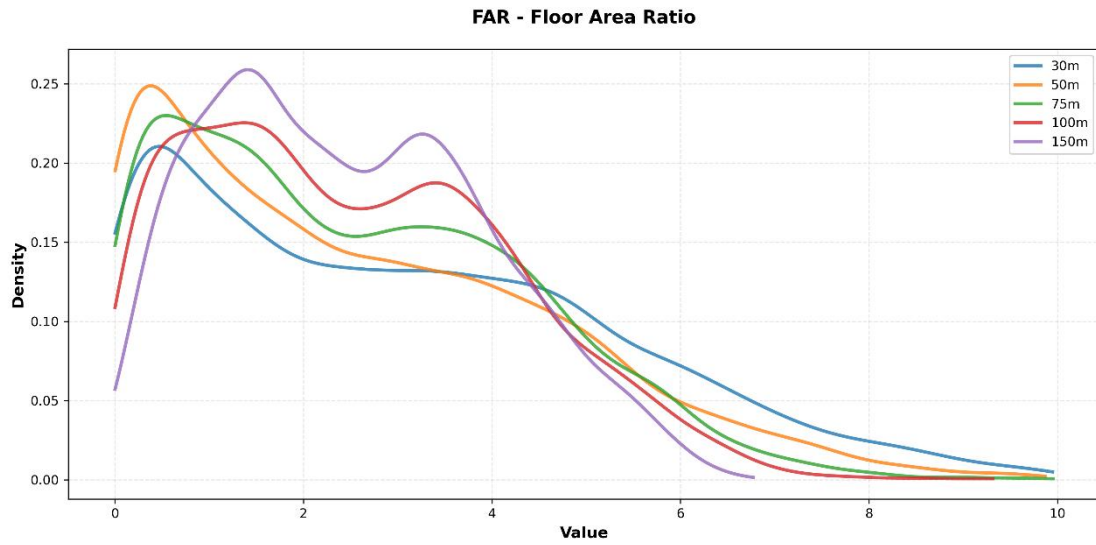


Figure 7-4 Statistical Distribution of Urban Form Parameter **FAR** (Figure by author.)

5) The distribution range of **D (Open Space Fragmentation Index)** is relatively wide, with a concentration around 0.055, indicating that the Mong Kok district has good spatial continuity and a low degree of fragmentation. This parameter is insensitive to grid cell size, with minimal variation in the mean value (only 2%) across different sizes, making it less susceptible to the influence of grid cell dimensions.

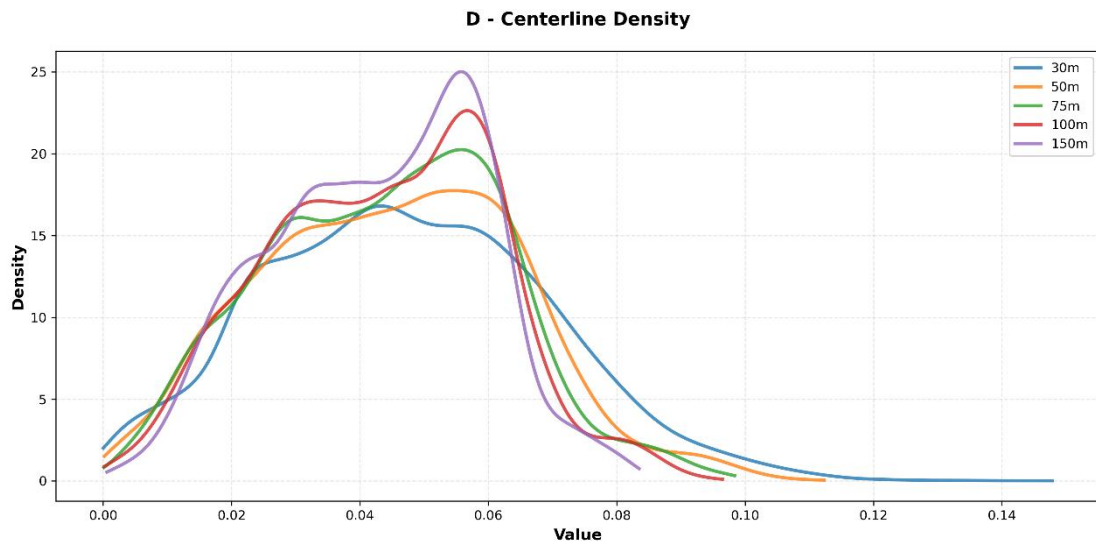


Figure 7-5 Statistical distribution of urban form parameter **D** (Figure by author.)

6) The distribution range of **W (Average Open Space Width)** spans from 0 to several thousand meters, with a concentration between 10 and 20 m, indicating that the ventilation

corridors in the Mong Kok district are exceptionally wide. The mean value is highest at a 30 m scale (35.4 m), influenced by extreme values within small-scale grids; when the grid cell size is $\geq 50 \text{ m} \times 50 \text{ m}$, the parameter distribution tends to stabilize (23 – 26 m), indicating that a $50 \text{ m} \times 50 \text{ m}$ scale is necessary to adequately reflect the width characteristics of open spaces in the Mong Kok district.

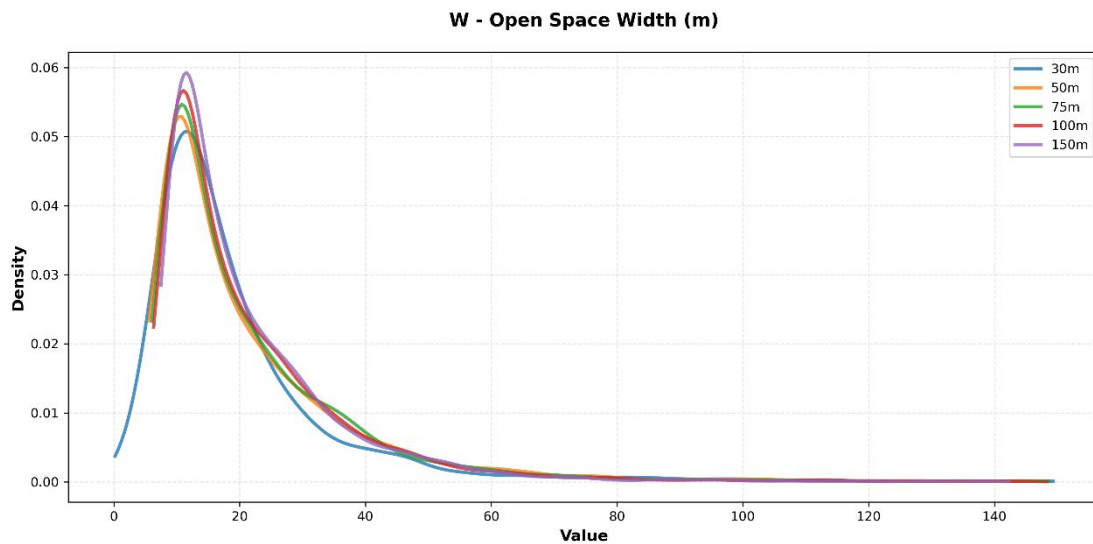


Figure 7-6 Statistical Distribution of Urban Form Parameter **W** (Figure by author.)

7) The distribution of **S (open space sinuosity)** is centered around 1. The parameter distributions vary significantly across different grid cell sizes. At 30 m, the results are anomalous due to the overly small computational scale; therefore, only the 50 – 150 m range is analyzed. As the grid cell size increases, the value gradually approaches and exceeds 1.0. When the grid cell size is $\geq 100 \text{ m} \times 100 \text{ m}$, the distribution stabilizes around 1.01, indicating that the sinuosity of open space is extremely sensitive to grid cell size and is the most sensitive parameter among all parameters.

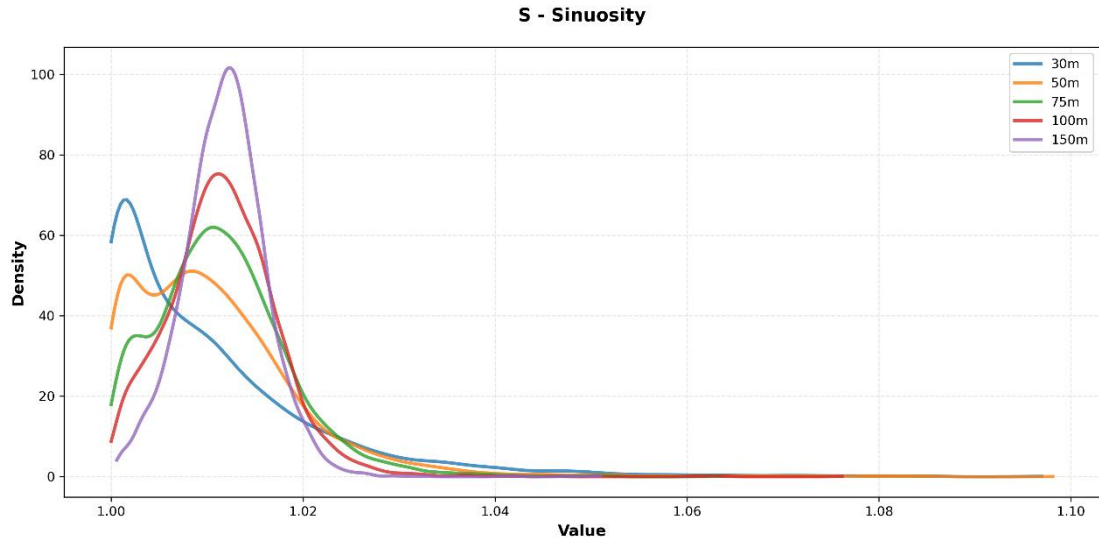


Figure 7-7 Statistical Distribution of Urban Morphology Parameter S (Figure by author.)

8) The distribution range of **SVF (Sky Visibility)** is relatively broad, with a median range of approximately 0.53 – 0.56 (53% – 56%), indicating excellent spatial openness in the Wangjiao neighborhood. As the grid cell size increases, the parameter continues to rise (by 5.4%), exhibiting mild sensitivity; within a larger observation range, the sky visibility becomes more expansive. Notably, when calculating SVF with a 30-meter radius, a large number of values of 1 were observed. This indicates that the 30-meter calculation area captures a significant amount of open space but does not accurately reflect the SVF value at that location; therefore, this parameter will be excluded during the subsequent generation of the prediction model.

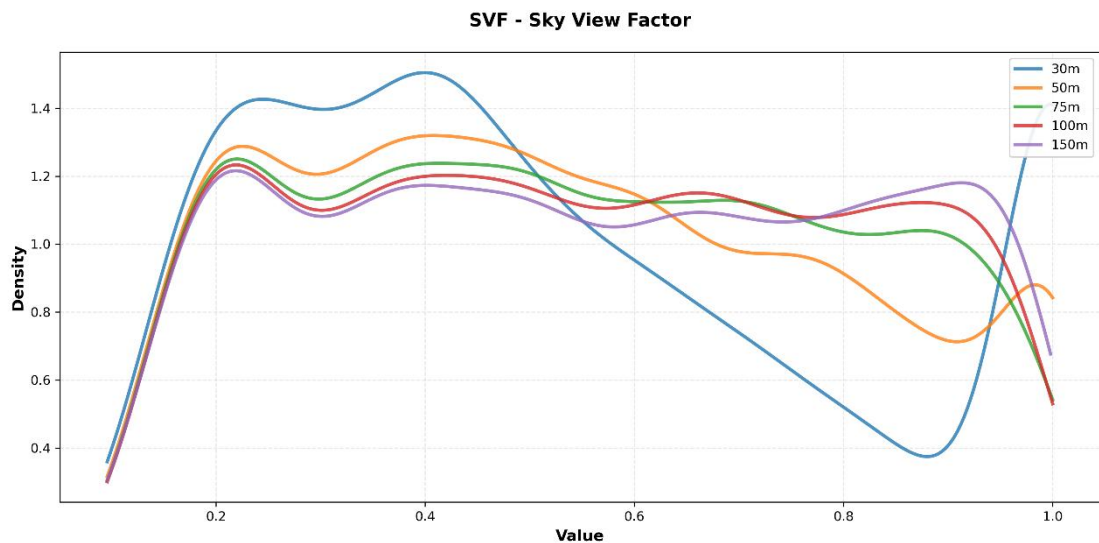


Figure 7-8 Statistical Distribution of Urban Morphology Parameter SVF (Figure by author.)

9) The distribution range of **FAI (Frontal Area Index of Podiums)** is relatively wide, with significant fluctuations (0.122 – 0.195), indicating that the podiums have a relatively weak blocking effect on airflow. The mean value is lowest at a 30-meter scale and highest at 150 meters, with a fluctuation range of 59.8%, reflecting the high sensitivity of podium morphological characteristics to grid cell size.

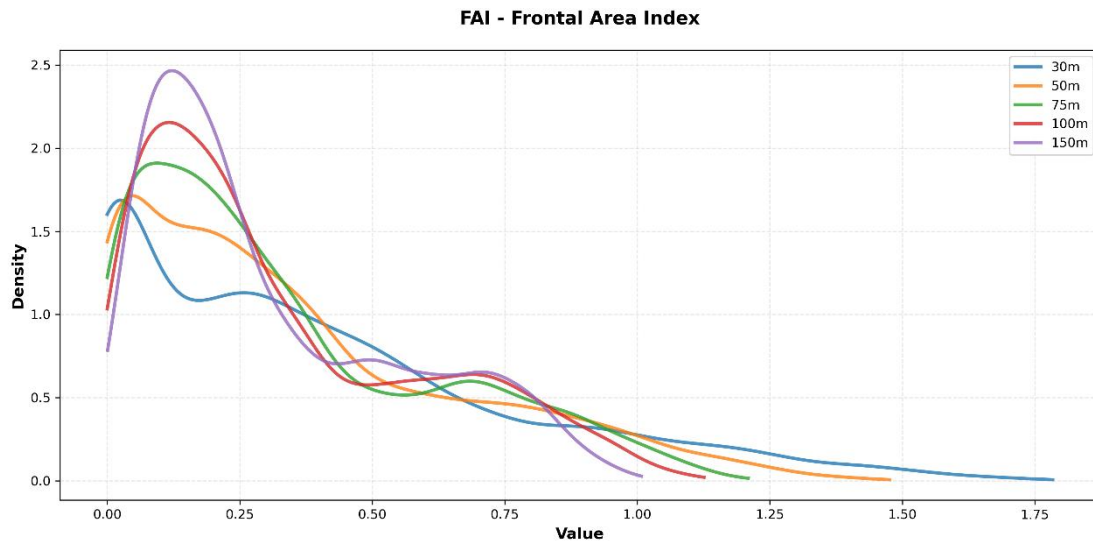


Figure 7-9 Statistical Distribution of Urban Morphological Parameter **FAI**

(Figure by author.)

10) The distribution range of λ_b (**building surface area ratio**) is relatively broad, concentrated between 1.28 and 1.87, indicating that the complexity of building surfaces in the Wangjiao district is moderate. As the grid cell size increases, the mean value of this parameter follows a trend of first decreasing and then increasing: it is highest at 30 m (1.87), drops to 1.71 at 50 m, further dropping to a minimum of 1.28 at 75 m. When the grid cell size is ≥ 100 m $\times$ 100 m, the parameter distribution stabilizes (between 1.52 and 1.56, with a fluctuation of only 2.6%), indicating that a 100 m $\times$ 100 m scale is necessary to adequately reflect the architectural surface complexity characteristics of the Mong Kok district. Small-scale grids (30 m) are prone to overestimating the surface area ratio due to the influence of local high-rise buildings, while medium-scale grids (75 m) may underestimate it due to insufficient spatial sampling. Large-scale grids (≥ 100 m), however, can more reliably capture the overall characteristics of building surfaces. The building surface area ratio reflects the multiple of the total surface area of building facades and roofs relative to the land area; a

higher value indicates a more complex building surface and greater wind resistance.

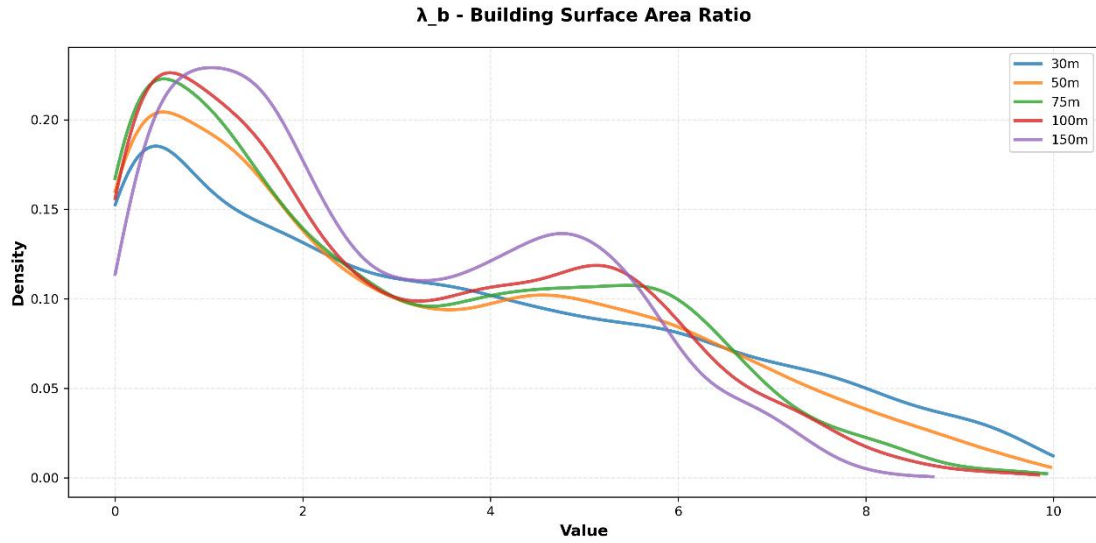


Figure 7-10 Statistical distribution of the urban form parameter λ_b (Figure by author.)

Based on the above quantitative analysis, this study recalibrated the criteria for sensitivity levels as follows: non-sensitive type, including the three parameters S, Hm, and W; mildly sensitive type, including only the D parameter; moderately sensitive type, including the C and λ_b parameters; and highly sensitive type, including the two parameters FAI and FAR. This quantitative classification system enables more precise identification of heterogeneity in distribution patterns, providing a more reliable basis for parameter selection and scale determination in subsequent pedestrian level wind environment prediction models.

