Hong Kong Housing Authority

Redevelopment of So Uk Estate

Air Ventilation Assessment – Initial Study Report

Issue 1 | 17 Feb 2015

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It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party.

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Executive Summary

Ove Arup and Partners Hong Kong Limited (Arup) is commissioned by Hong Kong Housing Authority (HKHA) to conduct Air Ventilation Assessment (AVA) study for the Redevelopment of So Uk Estate Phases 1 and 2 (the Development).

Located in the north part of Cheung Sha Wan district with a site area of around 7.7 hectares and a site level of some 10 to 46mPD, the So Uk Estate Redevelopment is situated on a relatively high ground next to Eagle's Nest (Tsim Shan) of height around 300m at the entire north of the Development. The built environment of the project area is relatively congested at the southwest and surrounded by some high-density building clusters such as Lai Po Garden (90mPD) and Beacon Lodge (120mPD) at the southwest, Lei Cheng Uk Estate (up to 85mPD) at the southeast, and Caritas Medical Centre (up to 85mPD) at the west, etc. There are also some low-rise structure and open space at the east of the Development, such as a few primary and secondary schools (max. 45mPD) at the east, So Uk Bus Terminal and Po On Road Playground.

This executive summary summarizes the findings from AVA Initial Study.

Objective

The objective of the study is to investigate the air ventilation performance of the proposed developments using the methodology for AVA as stipulated in the "Technical Circular No. 1/06 – Air Ventilation Assessments" (Technical Circular) and Annex A to the Technical Circular "Technical Guide for Air Ventilation Assessment for Developments in Hong Kong" (Technical Guide) jointly issued by Housing, Planning and Lands Bureau and Environmental, Transport and Works Bureau on 19th July 2006.

Study Scenarios

Two scenarios were evaluated in the AVA Initial Study.

1) Baseline Scheme – This was based on the layout of pre-demolished So Uk Estate (before the Redevelopment) with 15 numbers of mid-rise domestic blocks in a built form either long and linear or trident.

2) Proposed Scheme – 14 building blocks ranging from 6 to 41 storeys (some 40 to 123mPD in height up to upper roof floor) with optimised building disposition and provision of additional enhancement features for the wind environment.

Wind Availability

Based on the methodology of AVA, the site wind availability data was obtained from the Expert Evaluation for Cheung Sha Wan Outline Zoning Plan[1], which was calculated by mesoscale model (MM5) at the height of around 450m above the ground. The most frequent wind directions covering 78.2% of the annual wind frequency contains the prevailing winds. A summary of the frequency of the wind directions is shown in below.

Wind Direction	N	**NNE**	**NE**	**ENE**	**E**	**ESE**	**SE**	**SSE**	
Wind Frequency	2.7%	**8.2%**	**10.6%**	**17.6%**	**15.6%**	**9.0%**	**6.2%**	**6.0%**	
Wind Direction	**S**	SSW	SW	WSW	W	WNW	NW	NNW	**Sum**
Wind Frequency	**5.0%**	4.0%	4.2%	4.0%	2.5%	1.6%	1.5%	1.4%	**78.2%**

**The wind frequency showing in red colour represents the selected wind directions for the CFD simulation*

Results

	Baseline Scheme	Proposed Scheme
SVR	0.19	0.20
LVR	0.21	0.22

The results show that the values of local velocity ratio (LVR) and spatial velocity ratio (SVR) are marginally higher in the Proposed Scheme.

[1] Expert Evaluation and Advisory Report for Proposed Amendments to Cheung Sha Wan Outline Zoning Plan, Term Consultancy for Expert Evaluation and Advisory Services on Air Ventilation Assessment Services under Agreement No. PLNQ 35/2009, September 2010

Focus Area (FA)

No.	Focus Area	Test Points	Baseline Scheme Average VR	Proposed Scheme Average VR
1	**Caritas Medical Center**	O1-O11, P20-P25	0.16	0.14
2	**Wing Hong Street**	O12-O14	0.11	0.10
3	**Shun Ning Road**	O15-O16, O18, O20-O21, O23, O25-O26, O28, O30-O31	0.15	0.20
4	**Cheung Wah Street**	O17-O19	0.14	0.10
5	**Hing Wah Street**	O22-O24	0.14	0.19
6	**Po On Road**	P10-P19, O32-O33	0.16	0.21
7	**Cheung Fat Street**	P2-P10, O27-O29	0.19	0.20
8	**Po On Road Playground**	O34-O39	0.11	0.15
9	**Cheung Sha Wan Jockey Club Clinic & Kwong Lee Road**	O40-O43	0.17	0.18
10	**So Uk Bus Terminal**	P1, O44-O45	0.21	0.20
11	**Monte Carlton**	O65-O66	0.25	0.24
12	**Ching Cheung Road Highway**	O46-O64	0.40	0.39

The above table manifests that -

- Slightly higher LVR (0.22) and SVR (0.20) are found in Proposed Schemes than those in Baseline Scheme (0.21 in LVR and 0.19 in SVR).
- The Proposed Scheme achieves higher VRs than the Baseline Scheme in 6 focus areas: Shun Ning Road (FA3), Hing Wah Street (FA5), Po On Road (FA6), Cheung Fat Street (FA7), Po On Road Playground (FA8) and Cheung Sha Wan Jockey Club Clinic & Kwong Lee Road (FA9).
- On the other hand, the Baseline Scheme has higher VRs in 6 other areas: Caritas Medical Centre (FA1), Wing Hong Street (FA2), Cheung Wah Street (FA4), So Uk Bus Terminal (FA10), Monte Carlton (FA11) and Ching Cheung Road Highway (FA12).

These phenomena are due to the following spatial conditions:

- The Baseline Scheme has lower building heights and more continuous building blocks at the north, southwest/west and southeast/east end of the site, leading more of the prevailing wind towards FA11 and FA12 (due north), FA1, FA2 and FA4 (due west/southwest) and FA10 (due east);
- The Proposed Scheme possesses three types of wind-enhancing features added to the Development: wide building separations from 10m to more than 32m, stepping profile of building heights with downwash effect, five local air paths (plus the view corridor) and empty bays on G/F and at podium level.

1. Introduction

1.1 Project Background

Ove Arup & Partners Hong Kong Ltd (Arup) is commissioned by the Hong Kong Housing Authority (HKHA) to carry out an Air Ventilation Assessment (AVA) Study for the redevelopment of So Uk Estate Phase 1 & 2 (the Development).

1.2 Objective

The objective of this study is to evaluate the wind performance of the Development using the methodology of AVA, based on the "Housing Planning and Lands Bureau – Technical Circular No. 1/06, Environment, Transport and Works Bureau – Technical Circular No. 1/06" issued on 19th July 2006 (the Technical Circular) and "Technical Guide for Air Ventilation Assessment for Development in Hong Kong – Annex A" (the Technical Guide).

1.3 Study Tasks

The major task of this study is to carry out an AVA Initial Study to quantitatively assess the ventilation performance of the proposed Development and surrounding environment. The deliverables of this study can be summarised as follows,

- Evaluation of wind performance to gather typical wind characteristics,
- Assessment of ventilation performance in focus areas,
- Identification of general ventilation performance, problematic areas and design measures for air ventilation, and
- Recommendation of mitigation measures to rectify problematic areas if necessary.

2. Background Information

2.1 Site Characteristics

Located in the north part of Cheung Sha Wan district with a site area of around 7.7hectares and a site level of some 10 to 46mPD, the So Uk Estate Development is situated on a relatively high ground next to Eagle's Nest (Tsim Shan) of height around 300m at the entire north of the Development. The built environment of the project area is relatively congested at the southwest and surrounded by some high-density building clusters such as Lai Po Garden (90mPD) and Beacon Lodge (120mPD) at the southwest, Lei Cheng Uk Estate (up to 85mPD) at the southeast, and Caritas Medical Centre (up to 85mPD) at the west, etc. There are also some low-rise structure and open space at the east of the Development, such as a few primary and secondary schools (max. 45mPD) at the east, So Uk Bus Terminal and Po On Road Playground. Figure 1 shows the location of Project Site and its surrounding developments.

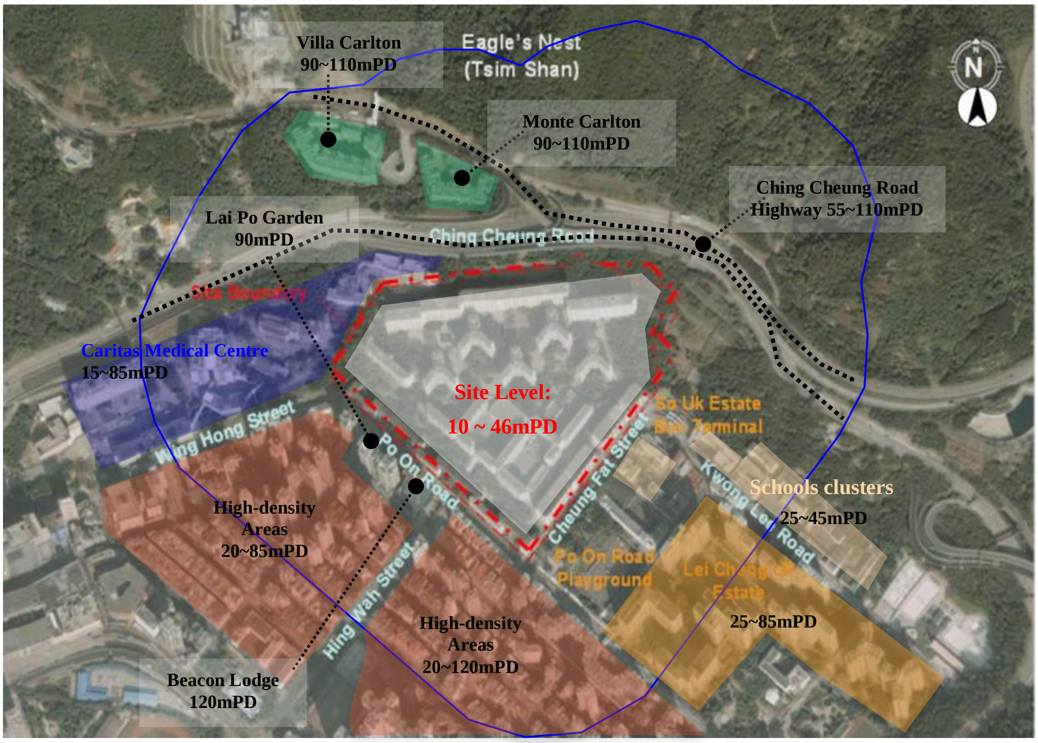

Figure 1 Location of Project Site and its surrounding developments around 2H-defined Surrounding Area (***blue lines***)

2.2 Study Scenarios

Two schemes, namely Baseline Scheme and Proposed Scheme, are evaluated in this study to identify the impact of wind performance on the Development and the neighbourhood.

2.2.1 Baseline Scheme

The original site condition (or the pre-demolished condition) that comprises 15 mid-rise domestic blocks (of level from 30 to 90mPD) of public housing estate is used as the Baseline Scheme. The built form of the blocks is either long and linear or trident, and with wide and continuous façade. Figure 2 shows the pre-demolished building layout of the So UK Estate and its surroundings, which together form a relatively congested built environment. A three-dimensional model of the Baseline Scheme of So Uk Estate is shown in Figure 3 to Figure 6.

Figure 2 Photo of original condition of the So Uk Estate

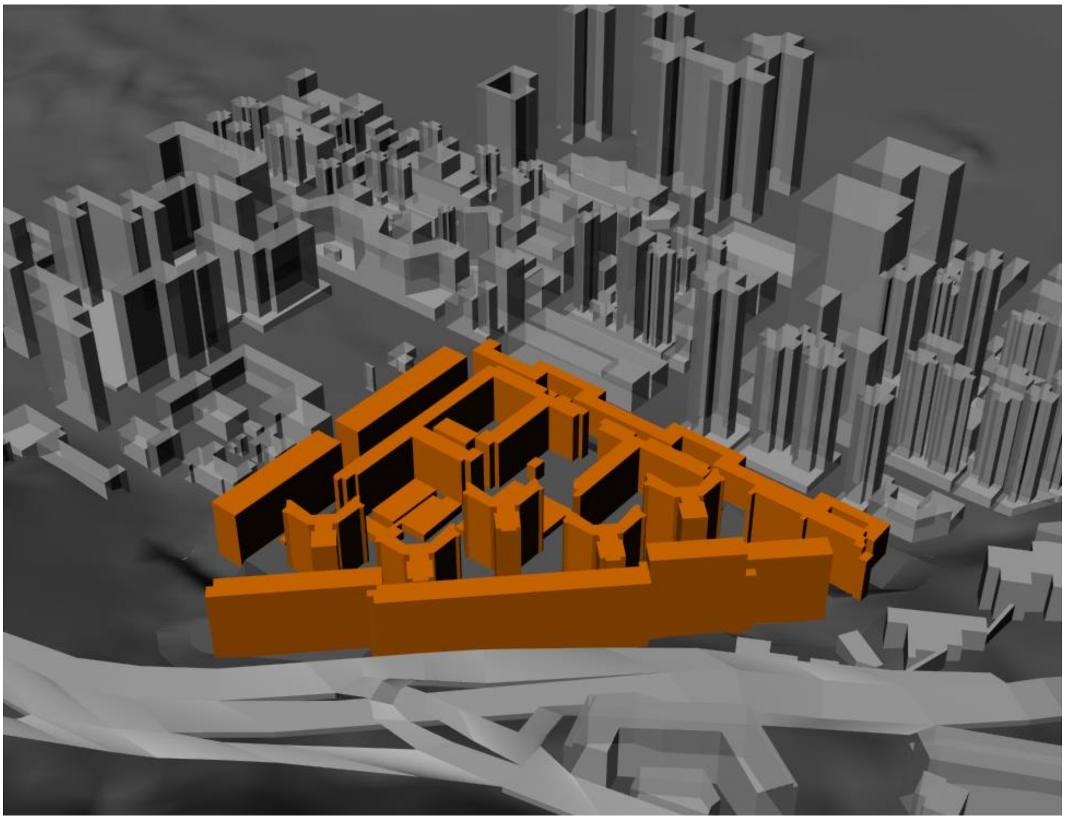

Figure 3 Northerly View of the Baseline Scheme of So Uk Estate

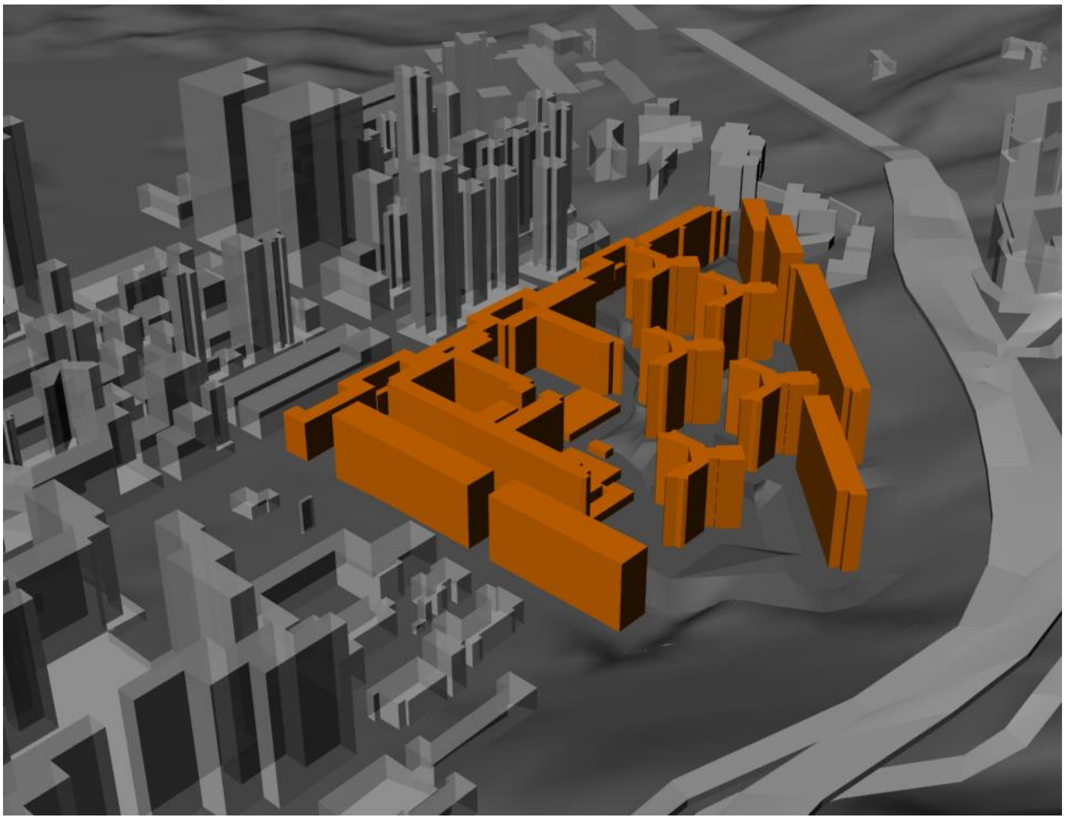

Figure 4 Easterly View of the Baseline Scheme of So Uk Estate

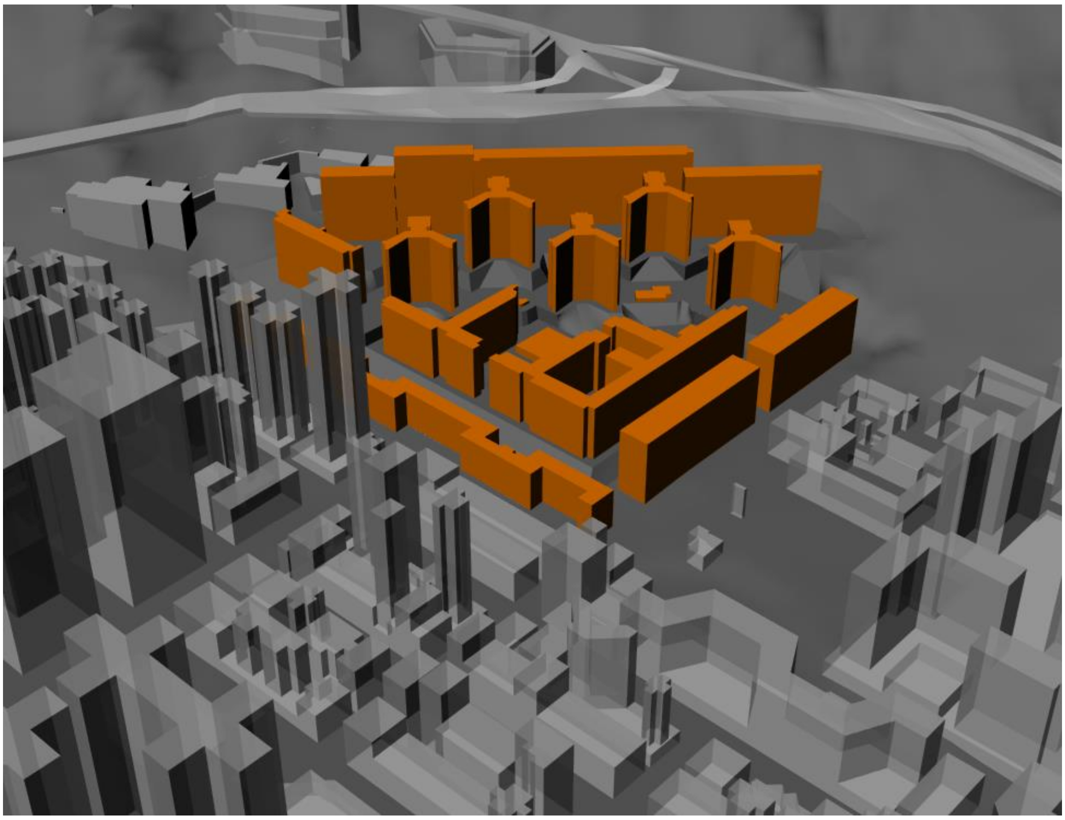

Figure 5 Southerly View of the Baseline Scheme of So Uk Estate

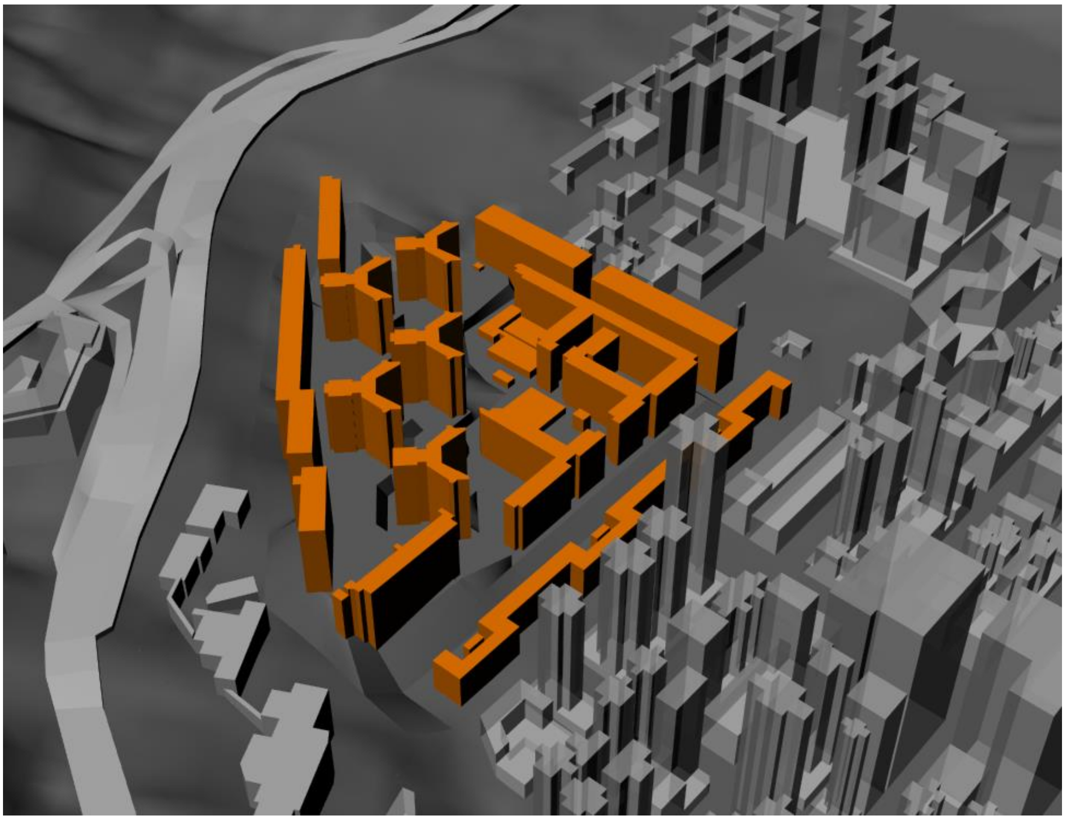

Figure 6 Westerly View of the Baseline Scheme of So Uk Estate

2.2.2 Proposed Scheme

Based on the maximum development potential of the Re-development, this design scheme is split into two Phases, Phase 1 (PH1) and Phase 2 (PH2). PH1 consists of 8 domestic building blocks, commercial and social welfares facilities. PH2 consists of 7 domestic blocks, carpark and retail blocks. Compared to the pre-demolished condition, the proposed building heights are higher, ranging from 6 to 41 storeys. In order to enhance the ventilation performance on the site, the following major features have been adopted:

- **Wide building separations** from 10m to more than 32m,
- **Stepping profile of building heights** created with lower building heights of Blocks 11-13 facing the east (E) prevailing wind directions to allow more air flow to reach inner areas of the site,
- **Empty bays on G/F** between Blocks 11A and 11B, Blocks 11B and 12, and inside Block 12,
- **Empty bays at podium level** of Blocks 11 and 12,
- **Five local air paths** created across the site in addition to the view corridor (stretched from Hing Wah Street as stipulated in the Outline Zoning Plan) by optimising the building disposition of Blocks 1 to 9 to favour the prevailing wind coming in from the northeast quadrant and heading towards the breezeways (Hing Wah Street, Cheung Wah Street and Wing Hong Street).

Details of these features with elevation drawings can be referred to Section 5 of this report. The overview of building heights and the building layout plan of the proposed scheme are shown in Table 1, Figure 7 and Figure 8.

Table 1 Building Heights of Proposed Scheme for So Uk Estate Redevelopment

Block	No. of Storeys	Height (mPD, up to UR/F)
1	23	112
2	23	112
3	22	109
4	29	123
5	29	120
6	25	108
7	41	143
8	41	143
9	28	108
10	6	42
11A & 11B	23	88
12	23	87
13	23	87
14A & 14B	21	87

Figure 7 Building Footprints of all 14 Residential Blocks in Proposed Scheme

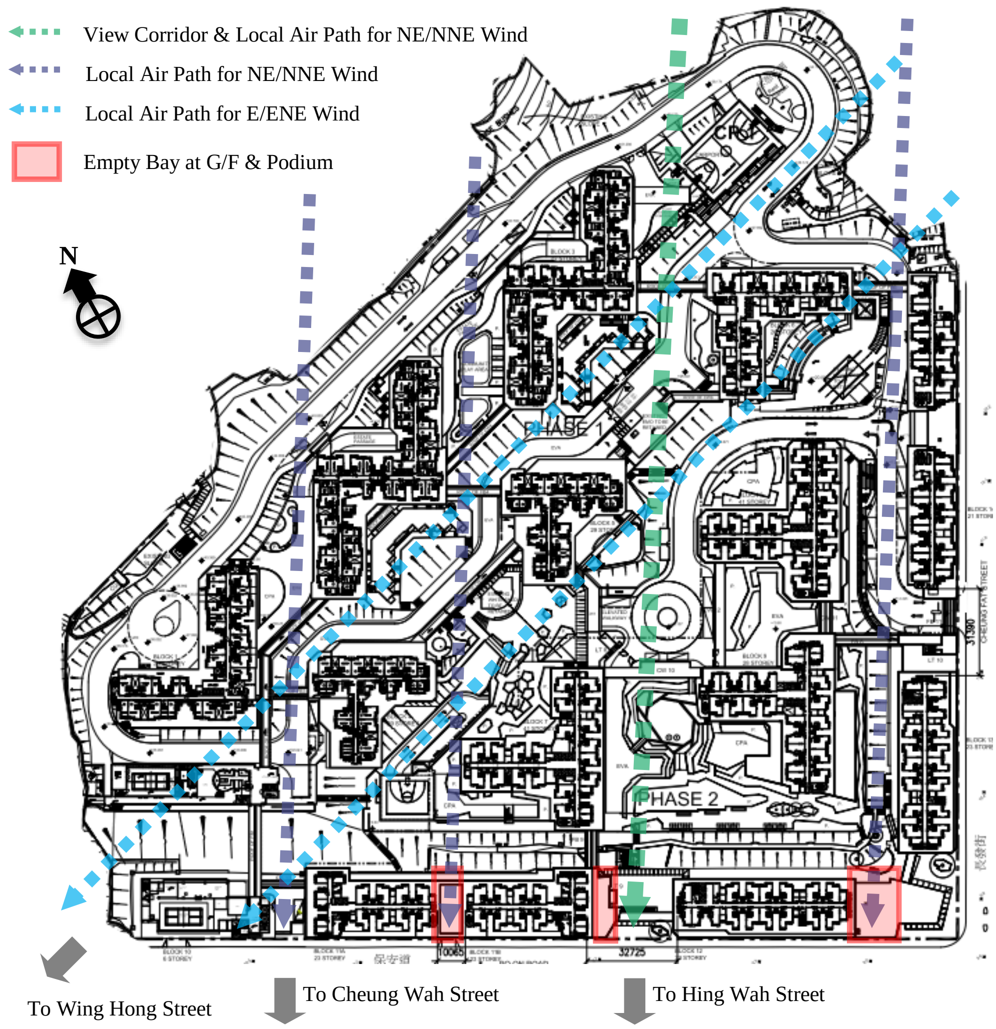

Figure 8 Building Layout of Proposed Scheme

The 3-dimensional model of Proposed Scheme is shown in Figure 9 to Figure 12.

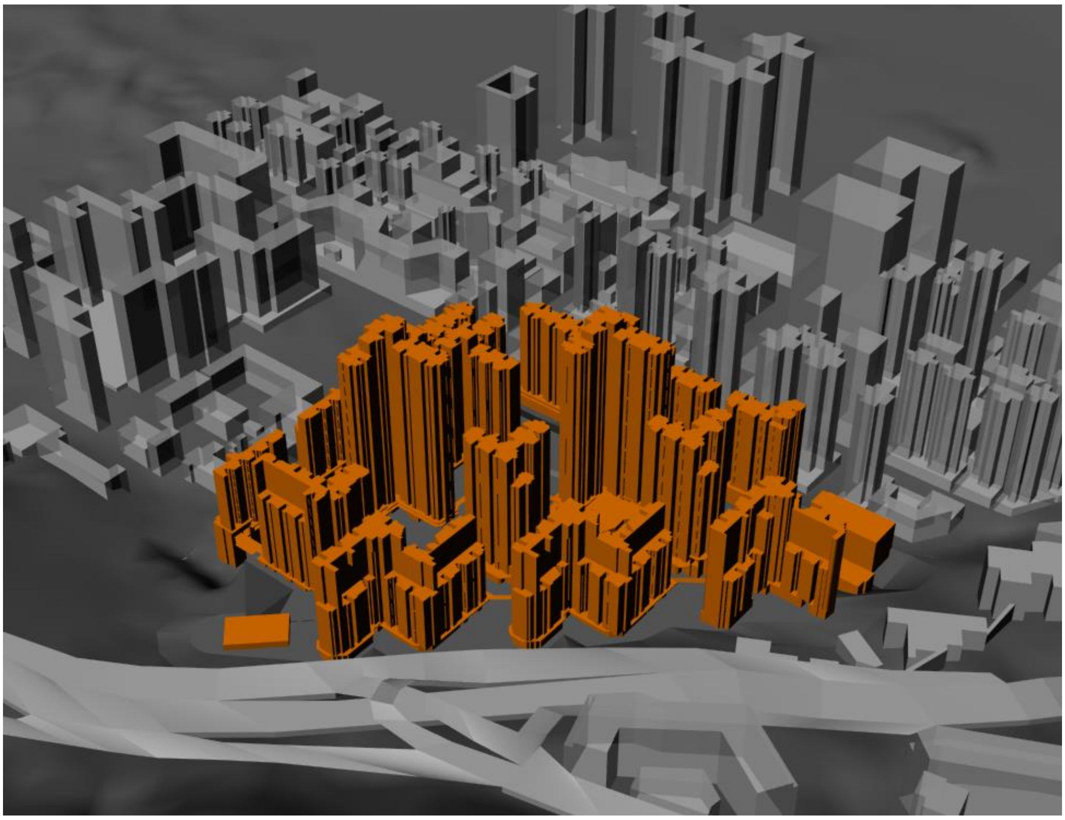

Figure 9 Northerly View of the Proposed Scheme of So Uk Estate

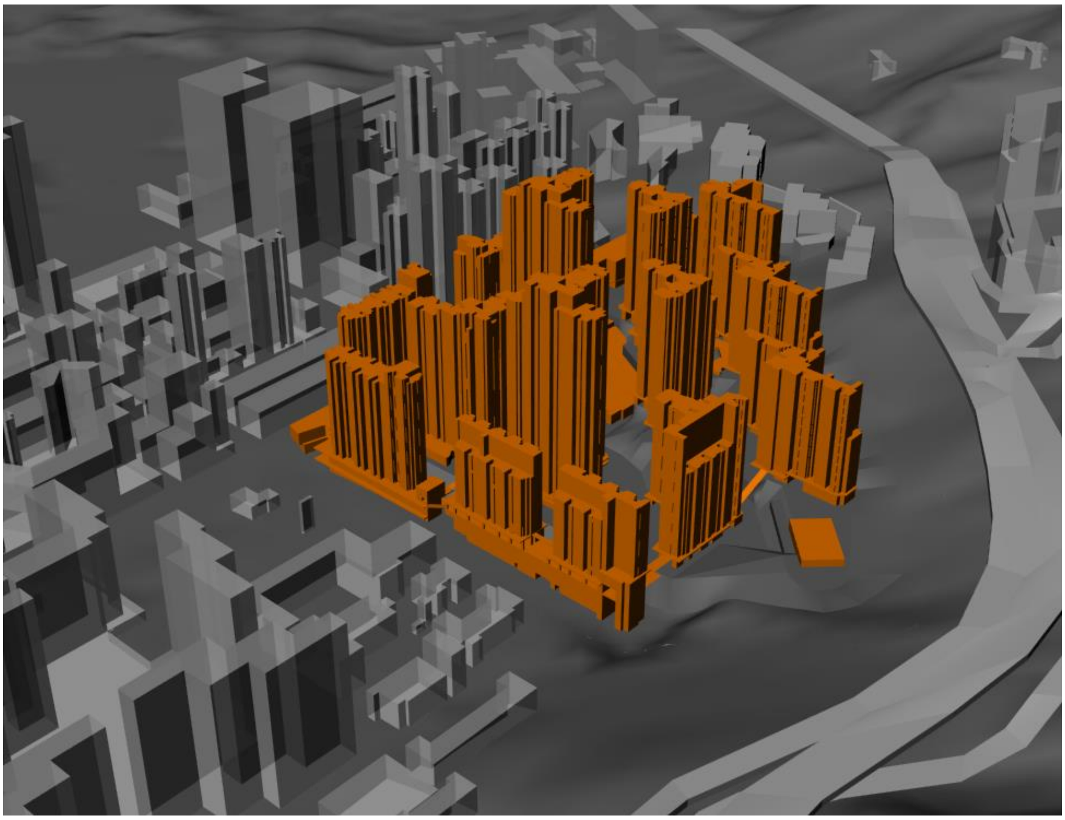

Figure 10 Easterly View of the Proposed Scheme of So Uk Estate

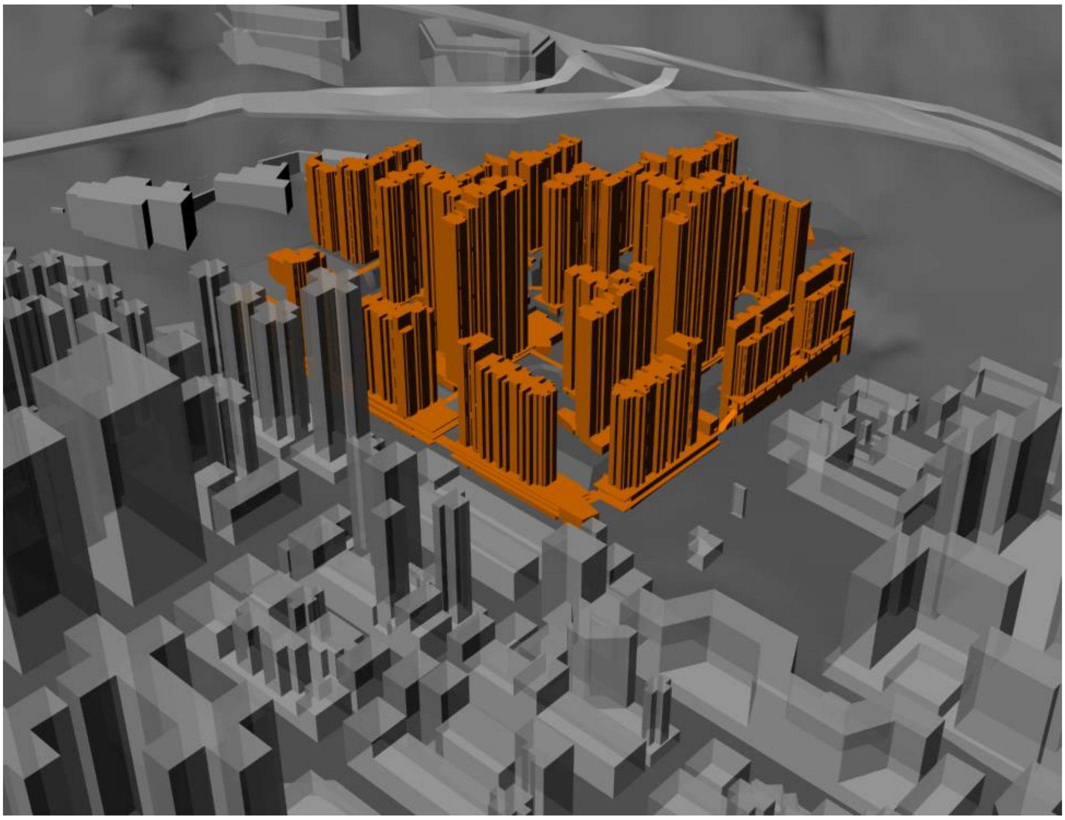

Figure 11 Southerly View of the Proposed Scheme of So Uk Estate

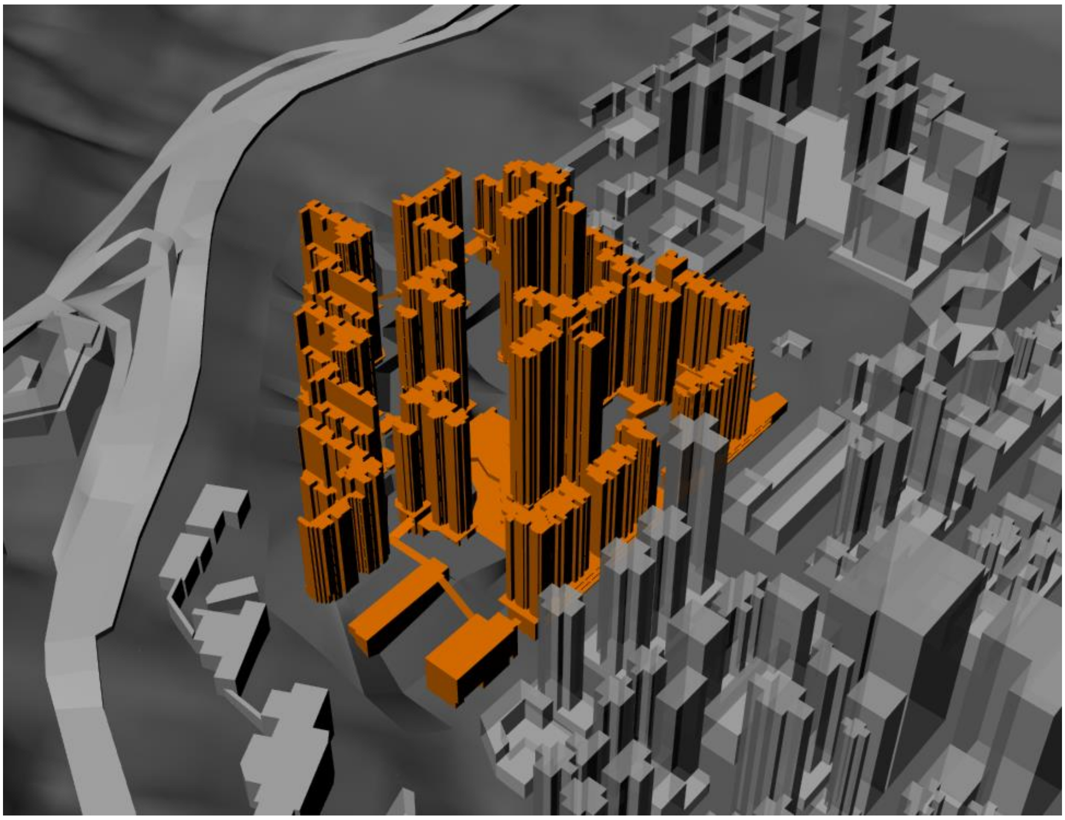

Figure 12 Westerly View of the Proposed Scheme of So Uk Estate

3. Methodology of AVA Study

3.1 Wind Availability

To investigate the wind performance of the development site, the characteristic of the natural wind availability of the site is essential.

3.1.1 Wind Directions

As stipulated in the Technical Guide, the site wind availability (V∞) was presented by using appropriate mathematical models (e.g. MM5 simulation). The site wind availability data were obtained from the Expert Evaluation for Cheung Sha Wan Outline Zoning Plan[2]. The wind availability data obtained from the MM5 simulation were utilised for the Initial Study, as shown in Figure 13 below. The wind frequency from each direction is tabulated in Table 2. A total of 8 climate conditions (i.e. NNE, NE, ENE, E, ESE, SE, SSE and S) accounting for 78.2% of the annual wind frequency are analysed to assess the ventilation performance of the Development. The wind directions selected for AVA simulation is shown in RED in Table 2.

Annual Wind (450mPD)

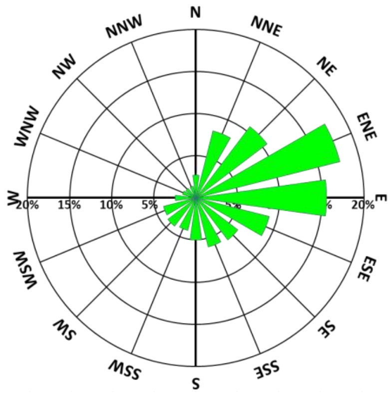

Figure 13 Windrose of the So Uk Estate by MM5 Wind Data

Table 2 Wind frequency table

Wind Direction	N	**NNE**	**NE**	**ENE**	**E**	**ESE**	**SE**	**SSE**	
Wind Frequency	2.7%	**8.2%**	**10.6%**	**17.6%**	**15.6%**	**9.0%**	**6.2%**	**6.0%**	
Wind Direction	**S**	SSW	SW	WSW	W	WNW	NW	NNW	**Sum**
Wind Frequency	**5.0%**	4.0%	4.2%	4.0%	2.5%	1.6%	1.5%	1.4%	**78.2%**

[2] Expert Evaluation and Advisory Report for Proposed Amendments to Cheung Sha Wan Outline Zoning Plan, Term Consultancy for Expert Evaluation and Advisory Services on Air Ventilation Assessment Services under Agreement No. PLNQ 35/2009, September 2010

3.1.2 Wind Profile

The wind profile, which considers the mean wind speed and the turbulence intensity, was taken as input parameters in the CFD models. The wind profile was assumed to follow the power law for specific terrains as given in Equation 1:

$$U_z = U_G \times \left(\frac{z}{z_G}\right)^n \qquad \text{Equation 1}$$

where U_G = reference velocity at height z_G

U_z = velocity at height z

z_G = reference height

z = height above ground

n = power law exponent

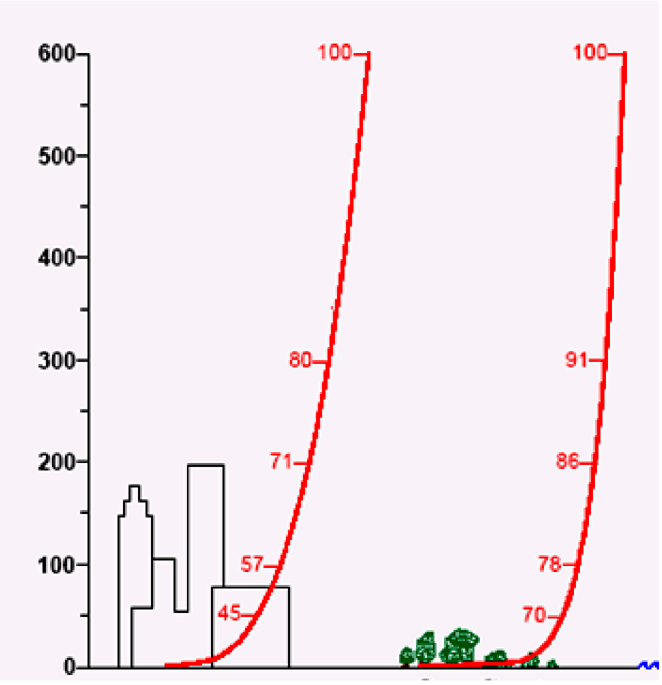

Figure 14 Wind Profile

Table 3 n-values for Different Terrains

Terrain crossed by approaching wind	n-value
Sea and open space	~0.15
Sub-urban or mid rise	~0.35
City center or high rise	~0.50

The power, *n*, is related to the ground roughness, which is determined by types of terrain. A larger value of the power n represents higher roughness of the ground e.g.

dense city/town area. Alternatively, smaller n represents lower ground roughness, e.g. the sea surface. With reference to the MM5 data of So Uk Estate, different values of *n* designated to different wind directions in this study are tabulated in Table 4.

Table 4 *n*-values applied in this study

Wind Direction	NNE	NE	ENE	E	ESE	SE	SSE	S
n value	0.15	0.15	0.15	0.35	0.35	0.35	0.35	0.35

In this study, the *n*-values were assumed to be 0.15 for the prevailing wind directions in the northeast quadrant and 0.35 for the rest in the simulations to represent the hilly but open topography in the north and the mid- to high-rise buildings from the east to south.

3.2 Study Area

3.2.1 Project Assessment Area and Surrounding Areas

With reference to the Technical Guide, the areas of evaluation and assessment should include all areas within the site, as well as the project's surrounding up to a perpendicular distance H from the project boundary ***(Assessment Area)***, where H is the height of the tallest building within the Development (H ≈ 120m).

Furthermore, the model area should include the surroundings of up to another H (i.e. 2H in total) beyond the Assessment Area ***(Surrounding Area)*** in order to take into account the effects of the surrounding buildings on the incoming wind profile and to predict the wind performance more precisely. The assessment and surrounding areas are shown in Figure 15 and the overview of buildings heights in Figure 1.

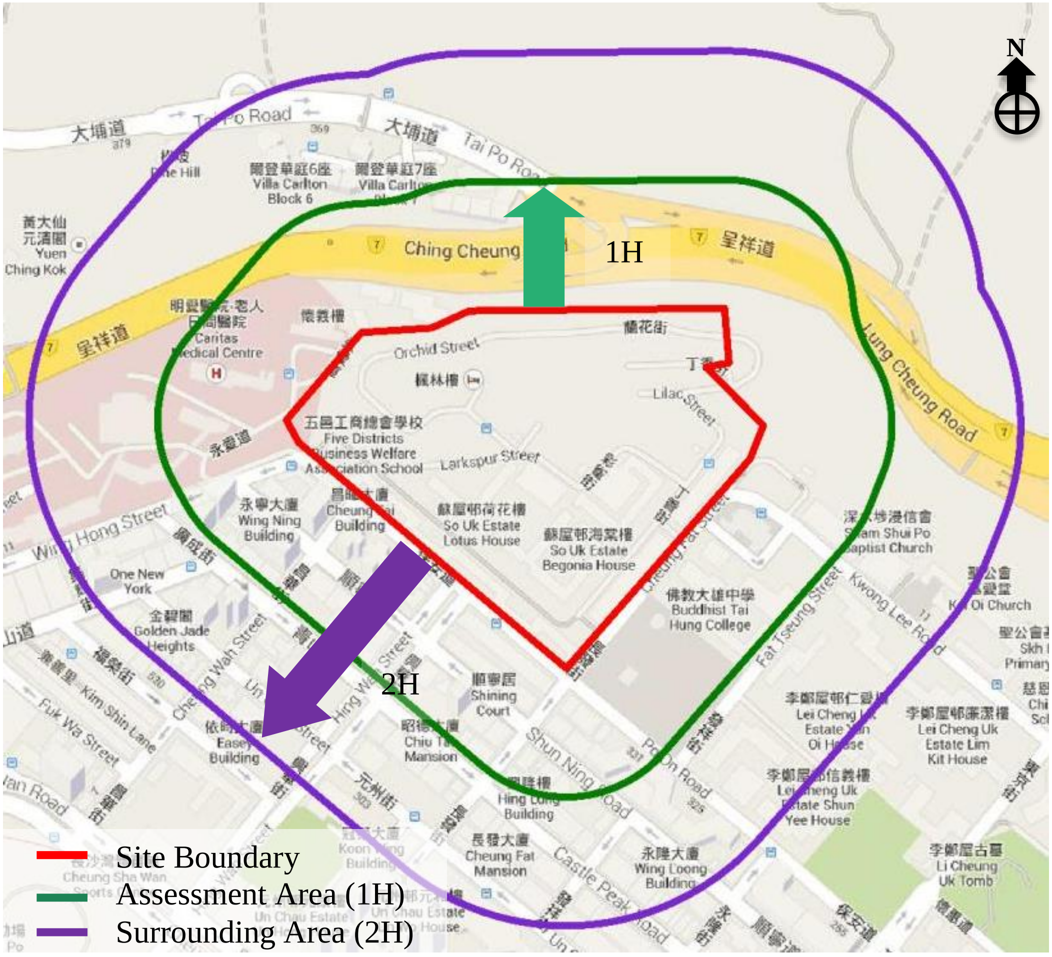

Figure 15 Site boundary, Assessment Area and Surrounding Area for the study

3.2.2 Assessment Parameter

As stipulated in the Technical Circular, the Wind Velocity Ratio (VR) was employed as an indicator of wind performance for the AVA of the proposed Development and the surrounding environment. The VR was calculated by using the following formula given in the Technical Circular:

$$VR = \frac{V_p}{V_\infty} \qquad \text{Equation 2}$$

where V_∞ = the wind velocity at the top of the wind boundary layer (typically assumed to be around 596m above the centre of the site of concern, or at a height where wind was unaffected by the urban roughness below).

V_P = the wind velocity at the pedestrian level (2m above ground) after taking the effects of buildings into account.

The average VR is defined as the weighted average VR by taking into account the percentage of occurrence of all considered wind directions. This gives a general idea of the ventilation performance at the considered location on an annual basis.

3.3 Test Point for Local and Site Ventilation Assessment

Test points were evenly placed along the site boundary and within the assessment area (1H) of the project site to determine the ventilation performance. There were two types of test points in the study:

3.3.1 Perimeter Test Points

Perimeter test points are the points positioned at the site boundary of the proposed Development. 35 perimeter points (***Green Spots***) are positioned alongside the site boundary as shown in Figure 16.

3.3.2 Overall Test Points

Overall test points are those points evenly positioned in the open space on the streets and places where are frequently accessed by pedestrians within the assessment area. 66 overall test points (***Pink Spots***) are shown in Figure 16.

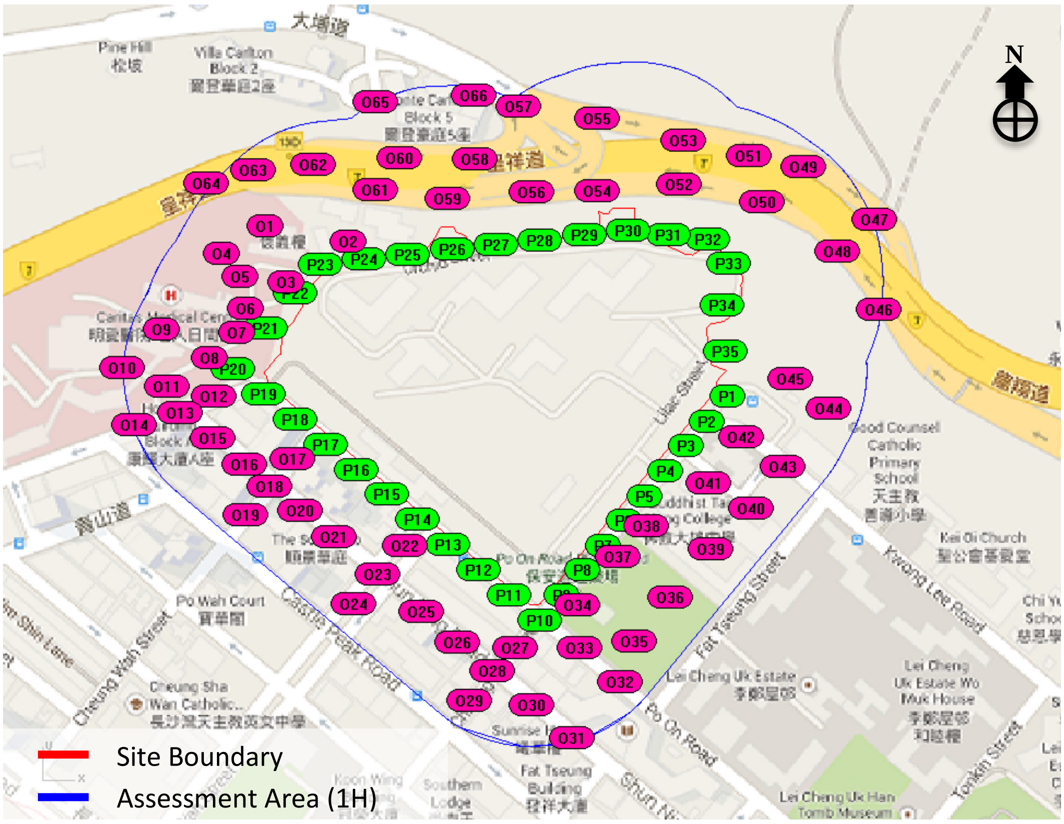

Figure 16 Location of perimeter and overall test points

3.4 Assessment Tools

Computational Fluid Dynamics (CFD) technique was utilized for this AVA initial Study. With the use of three-dimensional CFD method, the local airflow distribution could be visualised in detail. The air velocities within the flow domain, being affected by the site-specific designs and the surrounding buildings, have been simulated under the prevailing wind conditions round the year.

3.4.1 CFD Model

The size of the CFD model for this Study was approximately 2500m(L) x 2200m(W) x 1400m(max.H) and contained more than 4,000,000 cells. The whole CFD domain covered the entire development and the surrounding buildings.

The model also took information of the surrounding buildings and site topography via Geographical Information System (GIS) platform. Body-fitted unstructured grid technique was used to fit the geometry to reflect the complexity of the development geometry. A prism layer of 2m above ground (totally 4 layers and 0.5m each layer) was incorporated in the meshing so as to better capture the approaching wind (Figure 18). The expansion ratio was set at 1.3 while the maximum blockage ratio was less than 3%.

Finer grid system (with the smallest grid size of 0.5m per grid) was applied to the most concerned area based on preliminary judgement, while coarse grid system (more than 20m per grid at location far away from the site) was applied to the area of surrounding buildings for better computational performance while maintaining satisfactory results.

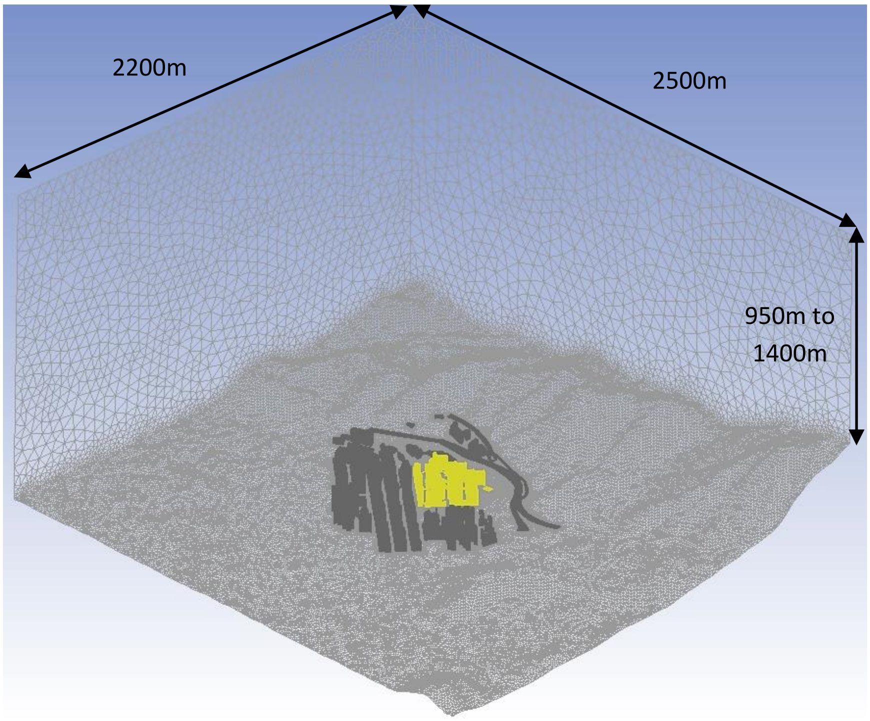

Figure 17 3D Mesh of Study Domain

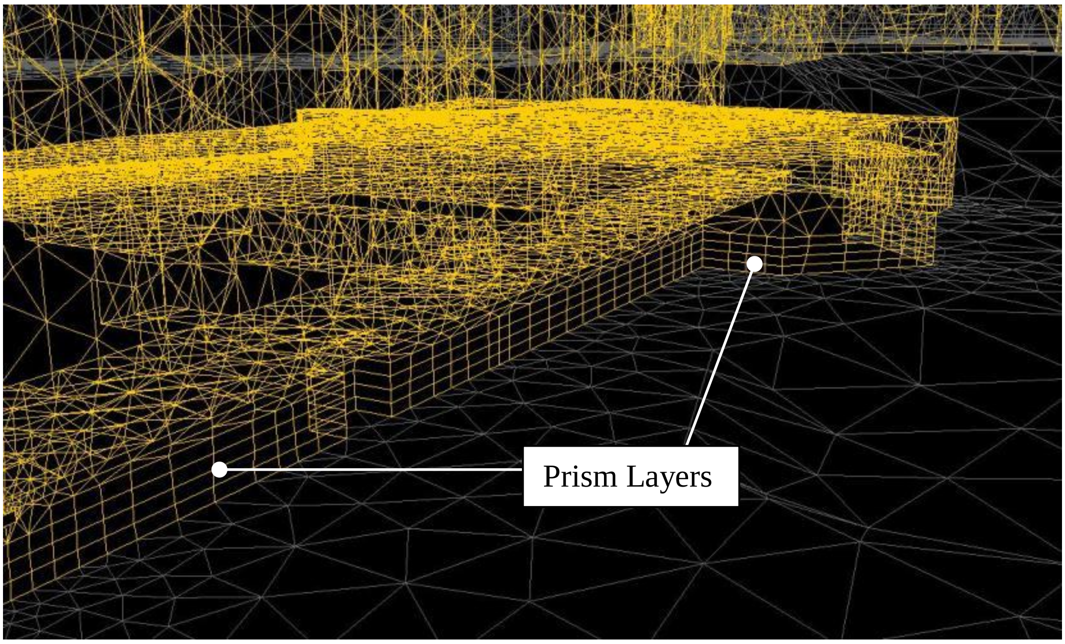

Figure 18 CFD Mesh and Prism Layers

3.4.2 Turbulence Model

As highlighted in recent academic and industrial research literatures by CFD practitioners, the widely used standard k - ε adequately model the effects of large scale turbulence around buildings and ignores the wind gusts leading to the relatively poor prediction in the recirculation regions around building. Therefore in this CFD simulation, realizable k- ε modelling method was applied. This technique provided more accurate representation of the levels of turbulence that could be expected in an urban environment.

3.4.3 Calculation Method

The Segregated Flow model solved the flow equations in an individual manner. The linkage between the momentum and continuity equations adopted the predictor-corrector approach. A collocated variable arrangement and a Rhie-and- Chow-type pressure-velocity coupling combined with a SIMPLE-type algorithm. A higher-order differentiating scheme was applied to discretize the governing equations. The convergence criterion was set to 0.001 on mass conservation. The calculation had repeated until the solution satisfied this convergence criterion. The prevailing wind direction as mentioned in Section 3.1.1 was set at the inlet boundary of the model with wind profiles as detailed in Section 3.1.2. The downwind boundary was set for the pressure with value of atmospheric condition. The top and side boundaries were set in symmetry. In addition, to eliminate the boundary effects, the model domain was built beyond the Surrounding Area as required in the Technical Circular.

3.4.4 AVA Study Parameters

CFD simulations have been conducted to study the wind environment. As specified in the Technical Circular, indicator of ventilation performance should be the Wind

Velocity Ratio (VR), defined as the ratio of the wind velocity at the pedestrian level (2m above ground) to the wind velocity at the top of the wind boundary layer. Site spatial average velocity ratio (SVR) and a Local spatial average velocity ratio (LVR) should be determined. The details of the assessment result for the scheme would be presented in the next section.

Table 5 Terminology of AVA Initial Study

Terminology	Description
Velocity Ratio (VR)	The velocity ratio (VR) represents the ratio of the air velocity at the measurement position to the value at the reference points.
Site spatial average velocity ratio (SVR)	The SVR ***(Green Spots)*** represent the average VR of all perimeter test points at the site boundary which identified in the report.
Local spatial average velocity ratio (LVR)	The LVR ***(Pink and Green Spots)*** represent the average VR of all points, i.e. perimeter and overall test points within assessment area identified in the report.

4. Results and Discussion

4.1 Overall Pattern of Ventilation Performance

The following sections would discuss the wind performance with the quantitative indicator, VR.

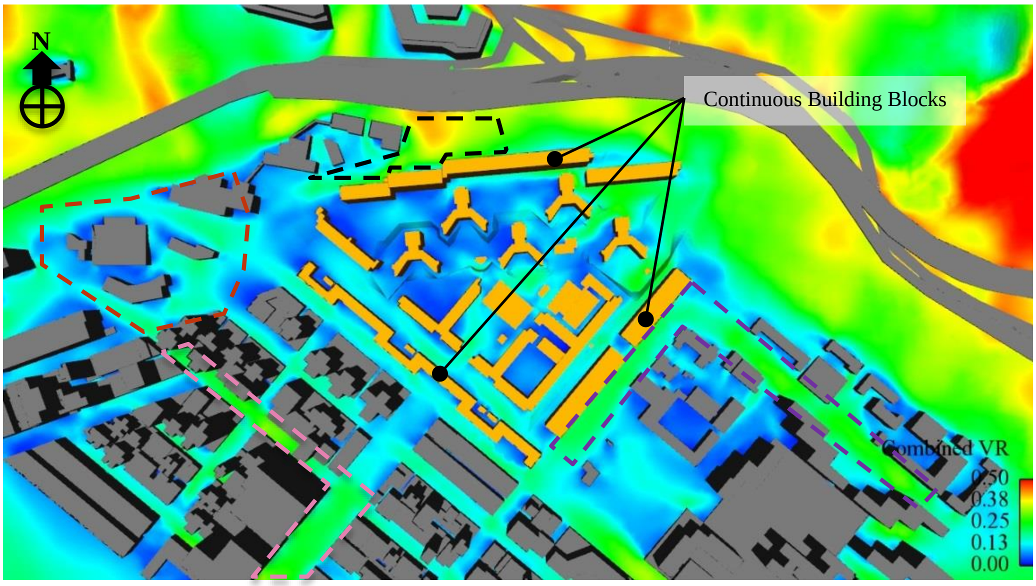

Figure 19 Contour Plot of Average VR at Pedestrian Level in Baseline Scheme

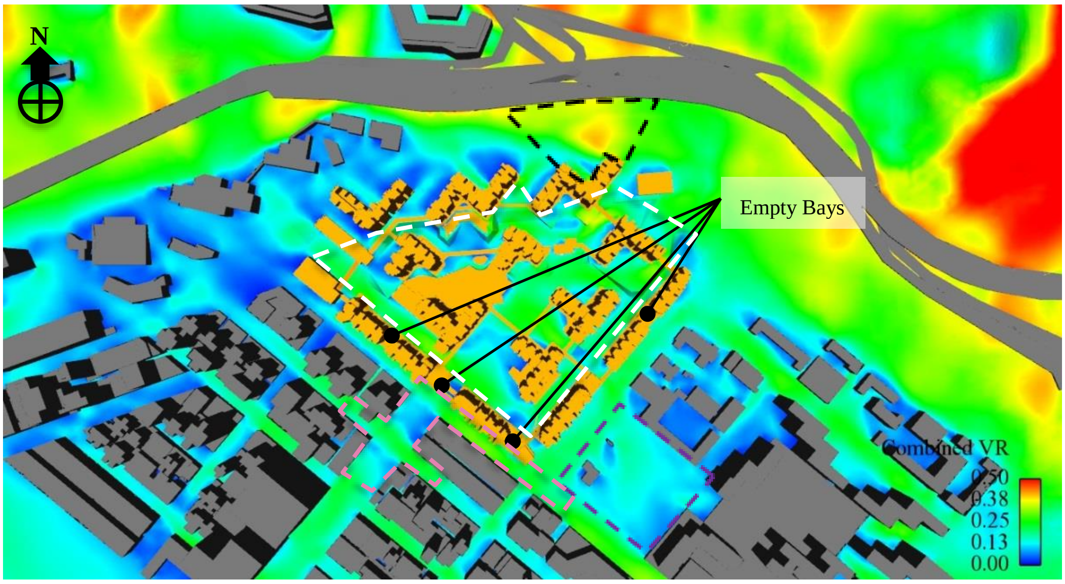

Figure 20 Contour Plot of Average VR at Pedestrian Level in Proposed Scheme

In the above time-weighted average VR contour plots, both schemes generally show a moderate divide in air ventilation performance at the pedestrian level.

- In the Baseline Scheme, wide continuous building masses of the outermost building blocks facing north (near Ching Cheung Road Highway), southwest (on Po On Road) and southeast (on Cheung Fat Street) downwashes some wind to the streets before or near them. As a result, Kwong Lee Road and Cheung Fat Street (**violet dotted lines** in Figure 19), parts of Caritas Medical Centre and Wing Hong Street (**brown dotted lines**), and some of the hilly slope enclosed by Ching Cheung Road Highway, Caritas Medical Centre and So Uk Estate (**black dotted lines)** are more ventilated than the same areas in the Proposed Scheme. The lower building heights of the original So Uk estate make it possible for the neighbouring tall buildings to capture and downwash more wind to the pedestrian level, leading to more ventilation in Castle Peak Road and far part of Hing Wah Street (**pink dotted lines**).

- In the Proposed Scheme, the inner streets and pedestrian areas within the site (**white dotted lines** in Figure 20) become more ventilated due to the increased permeability of the Development by means of wide building separations and empty bays on G/F and at podia. It is also because of these features that Po On Road and the crossroad of Castle Peak Road and Hing Wah Street (**pink dotted lines**) and Po On Road Playground (**violet dotted lines**) become better than those in the Baseline Scheme. Some of the wind is downwashed by the high building mass of Block 3 and thus, the nearby hilly slope between Block 3 and Ching Cheung Road Highway (**black dotted lines**) is also more ventilated.

4.2 Directional Analysis

All 8 wind directions simulated are further analysed below with complete sets of contour and vector plots of velocity ratios (VR) in both design schemes are shown in Appendix B and Appendix C.

4.2.1 North-north-easterly Wind

Baseline Scheme

Under the NNE wind condition, the Baseline Scheme exhibits a calm wind environment within the site area due to the presence of continuous building blocks along the site boundary. Some of the wind is thus downwashed and channelled by the frontage of the north building blocks to Caritas Medical Centre (**black dotted lines and arrow** in Figure 21).

Three other areas in the Baseline Scheme show stronger ventilation than those in the Proposed Scheme as a result of these continuous building blocks and the downwash effect. On Po On Road next to So Uk Estate (**brown dotted lines** in Figure 21), the prevailing wind is downwashed by the tall towers of Beacon Lodge and Lai Po Garden and then bi-directionally channelled by them and the south building blocks of So Uk Estate along Po On Road (**brown arrows**) and the upper part of Cheung Fat Street (**pink dotted lines**). The latter street also slightly benefits from the south continuous blocks where some of the prevailing wind inside the site area is directed out there in addition to the wind downwashed from Po Lai Court (**pink arrows**).

Proposed Scheme

With the disposition of building blocks and the consideration of local air paths in the Proposed Scheme, the inner streets and pedestrian areas of the Development (**white dotted lines** in Figure 22 in particular) are more ventilated than the Baseline. The prevailing blows down along the mountain to the east site boundary (**black arrows**) and is then diverted to the inner area of the Development and the open area of So Uk Bus Terminal and Kwong Lee Road (**black dotted lines**).

Further down southwest of the view corridor (the major local air path), the prevailing wind desceneds to Hing Wah Street and recirculates into Shun Ning Road and Castle Peak Road (**pink dotted lines and arrow** in Figure 22), making these areas better in wind environment.

Three other areas in this scenario slightly benefit from the overall building of the Development, one around part of Ching Cheung Road Highway near Villa Carlton (**blue dotted lines and arrows** in Figure 22), one at the crossroad of Castle Peak Road and Wing Hong Street (**violet dotted lines**) and one at the crossroad of Po On Road and Cheung Fat Street (**brown dotted lines and arrow**). The latter is partly assisted by the empty bays of Block 12 as well as the wide separation between Blocks 12 and 13 (**white arrow**).

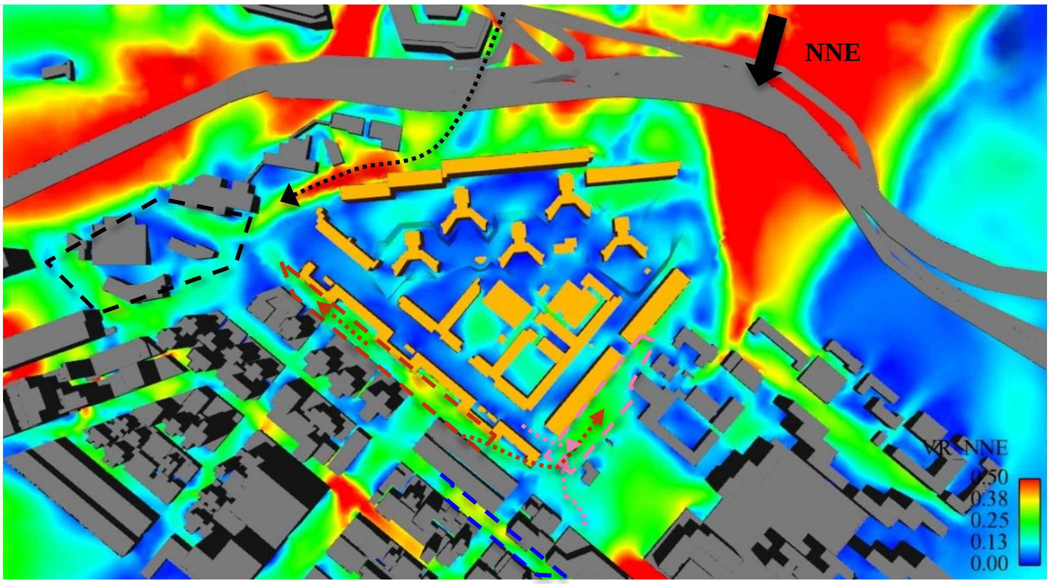

Figure 21 VR Contour Plot under NNE Wind Direction for Baseline Scheme

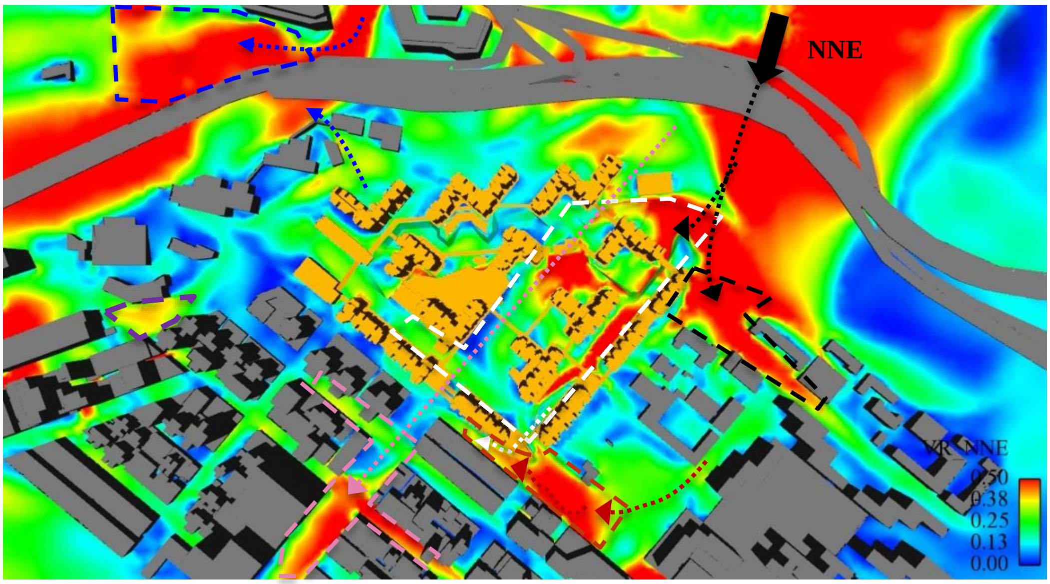

Figure 22 VR Contour Plot under NNE Wind Direction for Proposed Scheme

4.2.2 North-easterly Wind

Both schemes show relatively calm wind environment around the project site and the downwind region under the NE wind condition. Only a few differences are highlighted here.

Baseline Scheme

The continuous building blocks in the southwest favours more wind circulation in parts of Wing Hong Street near Caritas Medical Centre (**brown dotted lines and arrow** in Figure 23). Cheung Wah Street, Castle Peak Road and far part of Hing Wah Street (**pink dotted lines**) show better ventilation in the Baseline Scheme due to the relatively low building profile of the original So Uk Estate that helps those high neighbouring buildings in the downwind region capture and downwash the prevailing wind to the local pedestrian level.

Proposed Scheme

The higher building heights in the north (Blocks 2, 3, 6 & 8) capture more NE wind and downwash it to the frontage area (**black dotted lines and arrows** in Figure 24). At the open space between Ching Cheung Road Highway and the north of Caritas Medical Centre (**violet dotted lines**), slightly more prevailing wind blows over from Villa Carlton (**violet arrow**) with less resistance from the wind coming out of the Development.

Po On Road (**brown dotted lines**) outside Block 12 is more ventilated with the presence of empty bays in the building (**brown arrow**) and the wide separation between Blocks 12 and 13.

Meanwhile, a part of Shun Ning Road stretching from Hing Wah Street to Wing Hong Street and far part of Cheung Fat Street (**white dotted lines**) benefit from more wind circulation there mainly due to the downwash effect of tall buildings near the crossroads of Castle Peak Road, Hing Wah Street and Cheung Fat Street (**white arrows**).

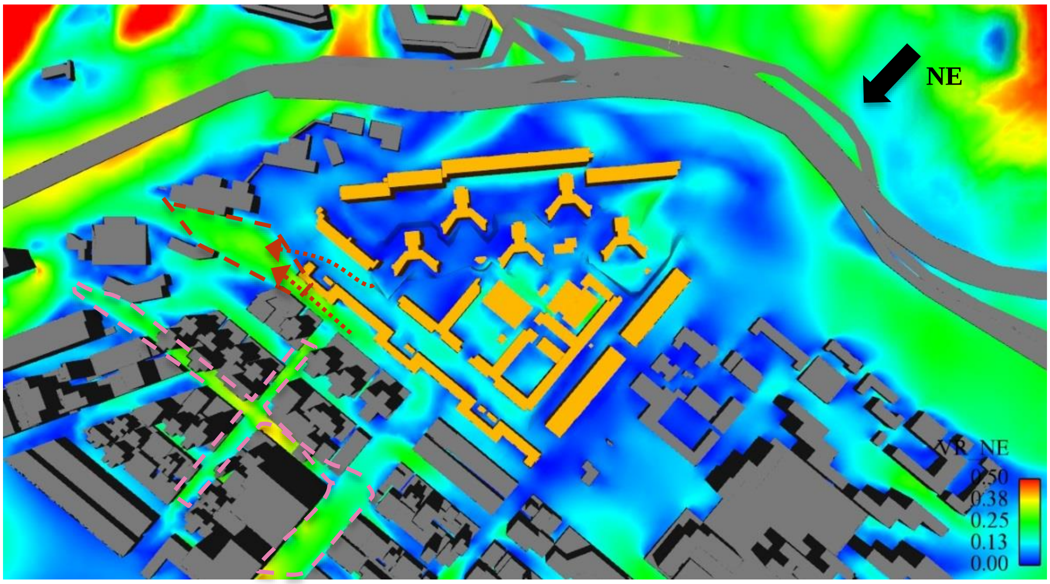

Figure 23 VR Contour Plot under NE wind for Baseline Scheme

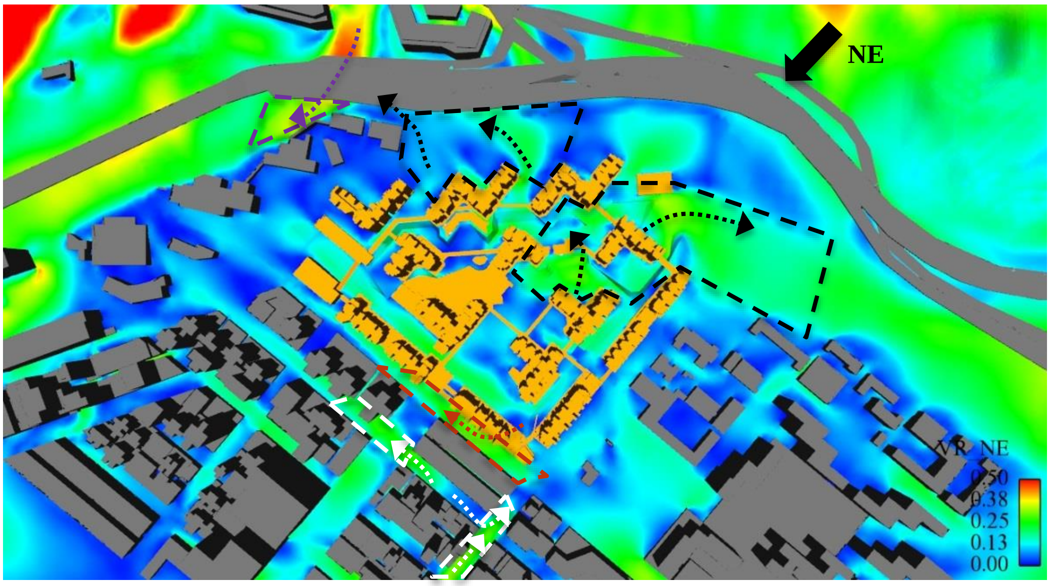

Figure 24 VR Contour Plot under NE wind for Proposed Scheme

4.2.3 East-north-easterly Wind

Baseline Scheme

Two areas of neighbourhood favour the continuous building blocks of the original So Uk Estate. Some of the ENE prevailing wind is directed by the north building blocks to Caritas Medical Centre and Wing Hong Street (**white dotted lines and arrow** in Figure 25) while the outermost building blocks on the southeast site boundary direct the wind to Cheung Fat Street and near part of Kwong Lee Road (**black dotted lines and arrow**).

Similar to the case of NNE wind, Cheung Wah Street, Castle Peak Road and far part of Hing Wah Street (**pink dotted lines** in Figure 25) show better ventilation in the Baseline Scheme due to the relatively low building profile of the original So Uk Estate that helps those high neighbouring buildings in the downwind region capture and downwash the prevailing wind to the local pedestrian level.

Proposed Scheme

Under the ENE wind condition, two of the local air paths function well by bringing the prevailing into the inner area of the Development (**black dotted lines and arrows**). Further down along them, the wind passes through the empty bays on G/F and podia of Blocks 11 and 12 (**white arrows**), which enhance the ventilation on the near part of Po On Road (**white dotted lines**).

At the crossroad of Hing Wah Street and Shun Ning Road (**pink arrow** in Figure 26), more wind comes from Po On Road because of the view corridor (major local air path) of the Development.

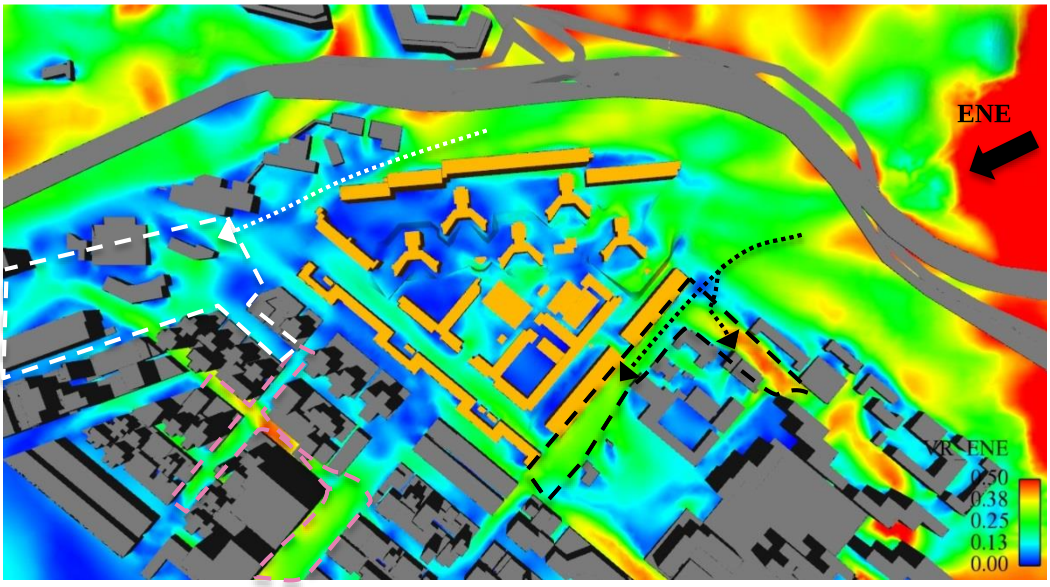

Figure 25 VR Contour Plot under ENE wind direction for Baseline Scheme

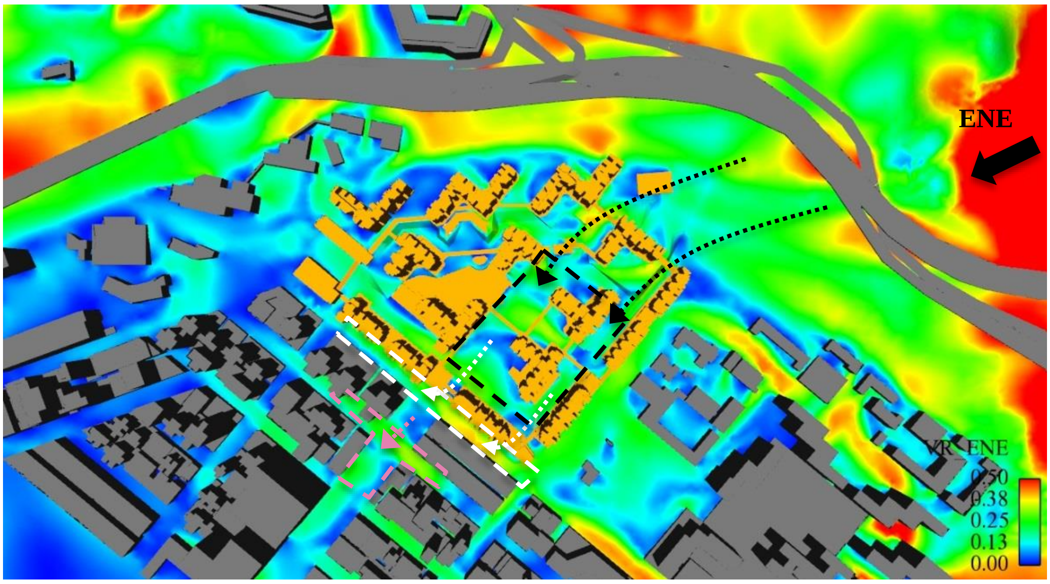

Figure 26 VR Contour Plot under ENE wind direction for Proposed Scheme

4.2.4 Easterly Wind

Baseline Scheme

In the north, the continuous building blocks of the original Estate directs the E prevailing wind to south part of Caritas Medical Centre and Wing Hong Street (**black dotted lines and arrow** in Figure 27); whereas at the southeast end of the Estate, similar effect takes place, directing the wind along Cheung Fat Street (**brown dotted lines and arrow**).

Some of the prevailing wind enters from the far part of Po On Road near Lei Cheng Uk Estate (**white dotted lines and arrow**), which makes the local area slightly more ventilated.

Proposed Scheme

With the increased permeability of the Development and a local air path for the E prevailing wind (**violet arrow** in Figure 28), the wind environment of the inner area of the Development and the east frontage of Caritas Medical Centre (**violet dotted lines**) is better than that in the Baseline Scheme.

At the north of the Development, the E prevailing wind rather blows along Ching Cheung Road Highway (**black arrow**) and goes down to the open area between the highway and the north of Caritas Medical Centre (**black dotted lines**).

The empty bays of Block 12 and the separation between Blocks 12 and 13 channel some wind to the near side of Po On Road (**white dotted lines and arrow**) while the view corridor of the Development and the empty bays between Blocks 11B and 12 encourage more flow along Hing Wah Street (**pink dotted lines and arrows**).

Blocks 9, 14A and 14B create a stepping profile of building heights that is able to capture more E wind at a high level, downwash it to the pedestrian level of the inner area of the Development and directs it out to Po On Road Playground through the gap between Blocks 13 and 14 (**brown dotted lines**). The wind then merges with the other coming from the upwind region of Cheung Fat Street (**brown arrows**).

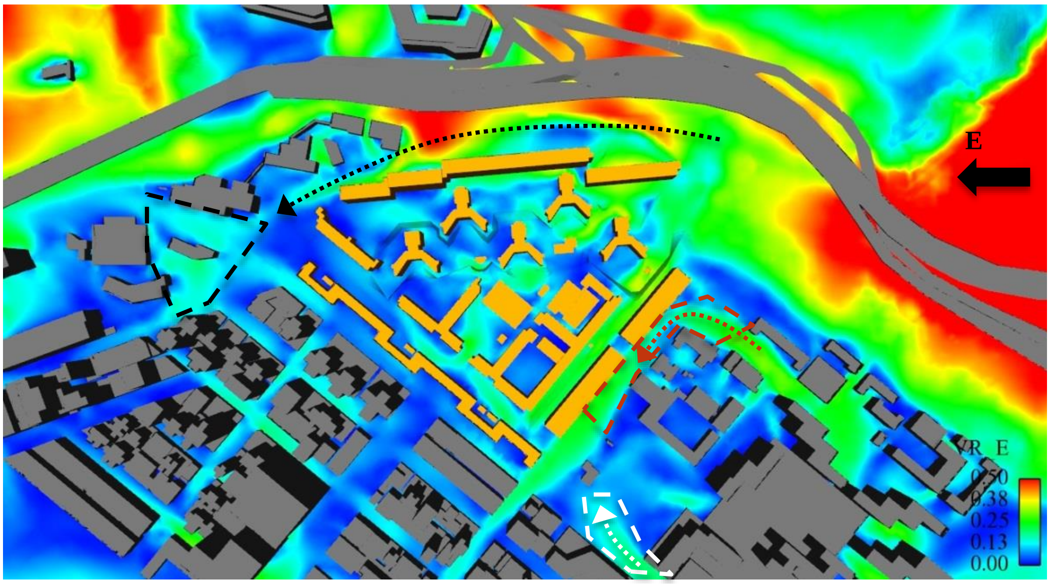

Figure 27 VR Contour Plot under E wind direction for Baseline Scheme

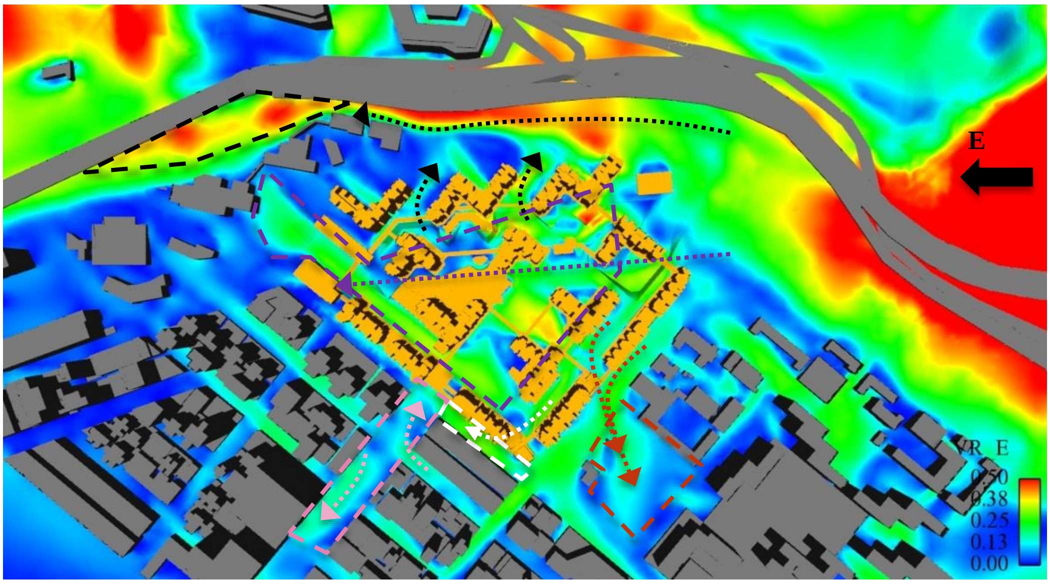

Figure 28 VR Contour Plot under E wind direction for Proposed Scheme

4.2.5 East-south-easterly Wind

Baseline Scheme

With the north continuous building blocks, the original Estate squeezes the ESE prevailing wind in the north and directs more of it (**black arrows** in Figure 29) to the east end of Caritas Medical Centre and the open space around Yuen Ching Kok Temple (**black dotted lines**).

At the west / southwest end of the Estate, the prevailing wind is directed by both inner and outer sides of the continuous building blocks on Po On Road to the central part of the hospital and Wing Hong Street (**violet dotted lines and arrows**).

At the east end of the original Estate (**white circle**) and Kwong Lee Road (**brown dotted lines**), the ESE wind finds it easier to pass through (**white arrow**) as the open area there is wider than that in the Proposed Scheme.

Proposed Scheme

Instead, the more dispersed and higher building blocks of the Proposed Scheme direct and downwash more of the prevailing wind to the pedestrian level of the central inner area of the Development (**white circle and arrows** in Figure 30), making it slightly more ventilated and larger in effective area.

Similar to the case of E wind, Blocks 9 and 14 downwash the ESE wind to the pedestrian level and direct it to Po On Road Playground (**brown box and arrows**).

Meanwhile, two other areas in the Proposed Scheme benefit from the design of empty bays under the ESE wind condition. One lies on the inner side of Blocks 11 and 12 towards the central part of Caritas Medical Centre (**black dotted lines**) and the other at the corner of Cheung Fat Street and Po On Road (**violet dotted lines**). A portion of the wind on Po On Road is diverted to the former area by the empty bays of Block 11 (**black arrows**) while some other wind from the inner side of Blocks 13 is directed to the latter area by the empty bays of Block 12 (**violet arrows**).

Some of the wind along Cheung Fat Street further goes down to the crossroad with Shun Ning Road and merges with the prevailing wind there to make the local part of the latter road slightly more ventilated (**pink dotted lines and arrow**).

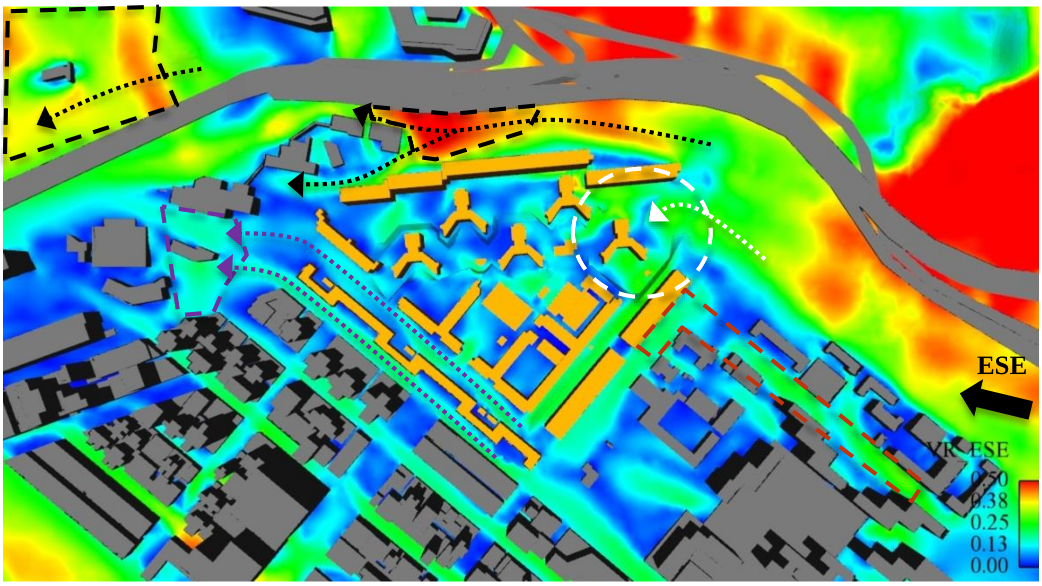

Figure 29 VR Contour Plot under ESE wind direction for Baseline Scheme

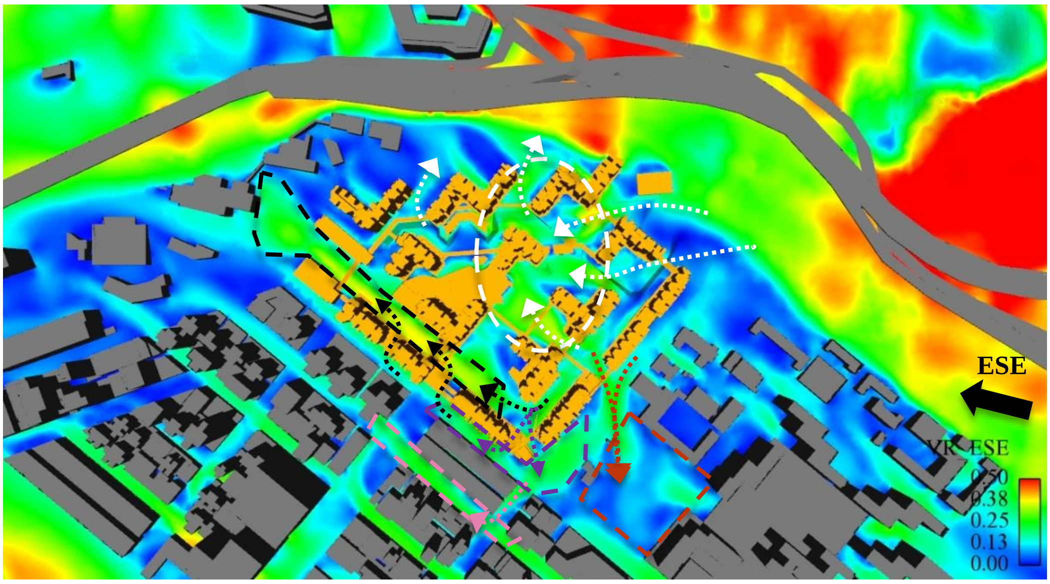

Figure 30 VR Contour Plot under ESE wind direction for Proposed Scheme

4.2.6 South-easterly Wind

Under the SE wind condition, the wind environments of both schemes, particularly the inner area of the Estate, look similar to each other except two neighbouring areas in the west/northwest and south/southeast.

Baseline Scheme
With the north continuous building blocks of the original Estate, more prevailing wind (**black arrows** in Figure 31) is squeezed into the north hilly open space stretching from Monte Carlton to Yuen Ching Kok Temple along Ching Cheung Road Highway (**black dotted lines**).

Similar to that in the ESE wind condition, the west / southwest continuous building blocks on Po On Road channel the prevailing wind on both of their inner and outer sides to the west of Caritas Medical Centre (**white dotted lines and arrows**).

Proposed Scheme
Similar to the scenarios of E and ESE prevailing wind, the SE wind is downwashed by the Blocks 9 and 14 to the pedestrian and ultimately directed to Po On Road Playground (**brown dotted lines and arrows** in Figure 32).

In the meantime, the slightly windier environment at the crossroad of Cheung Fat Street and Po On Road drives a portion of wind down one street to Shun Ning Road, leading to better ventilation across the whole street as well as a part of Wing Hong Street (**pink dotted lines and arrow**).

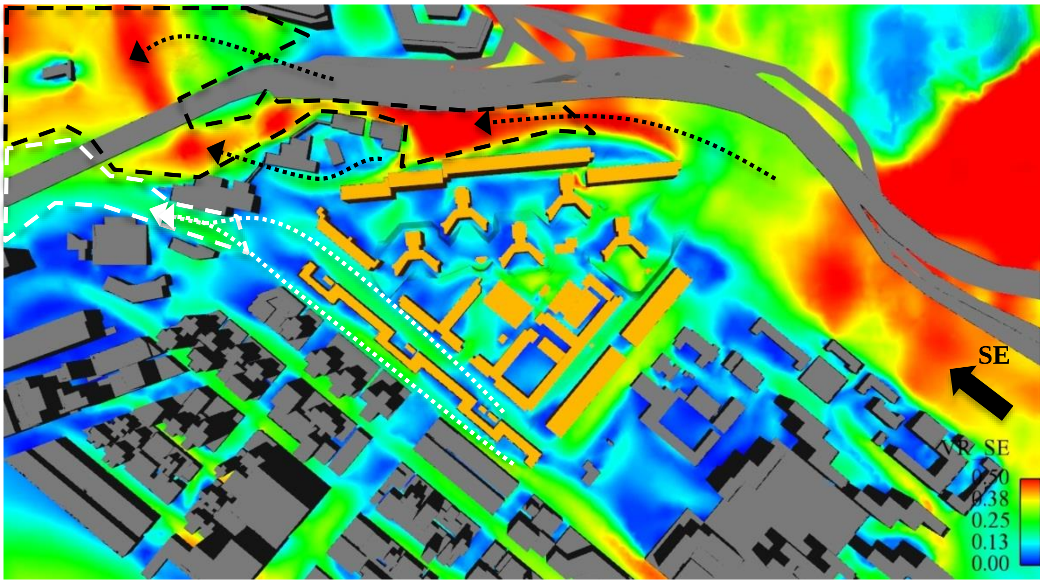

Figure 31 VR Contour Plot under SE wind direction for Baseline Scheme

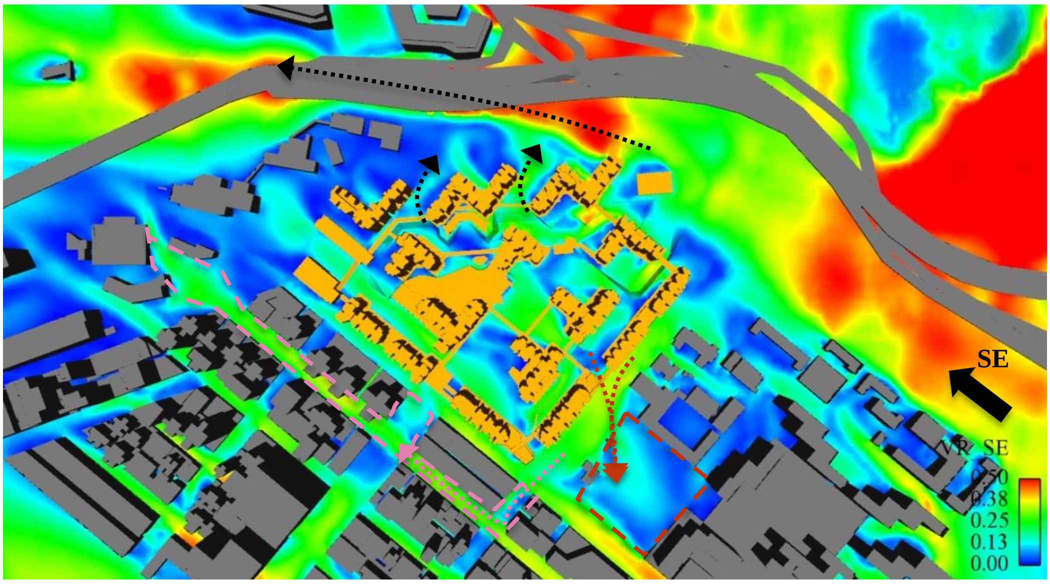

Figure 32 VR Contour Plot under SE wind direction for Proposed Scheme

4.2.7 South-south-easterly Wind

<u>Baseline Scheme</u>
Under the SSE wind condition, the north continuous building blocks of the original Estate squeeze the prevailing wind into the north hilly open space along Ching Cheung Road Highway, leading to better ventilation at the north of Caritas Medical Centre and the frontage of Villa Carlton (**black dotted lines and arrows** in Figure 33).

Similar to the situation under the ESE and SE wind conditions, the west / southeast continuous blocks on Po On Road channel the prevailing wind on both of their inner and outer sides towards the west end of the hospital and the open space further due west (**white dotted lines and arrows**).

<u>Proposed Scheme</u>
With higher towers of Blocks 1 to 7 in this design scheme, more SSE prevailing wind is captured and downwashed to the pedestrian level, making the inner area of the Development (**black circle** in Figure 34) better in ventilation than the Baseline Scheme.

The empty bays of Block 12 divert some wind from the inner area of the Development (**brown arrow**) to the other side of the building on Po On Road (**brown dotted lines**, making the local area more ventilated than that in the Baseline Scheme.

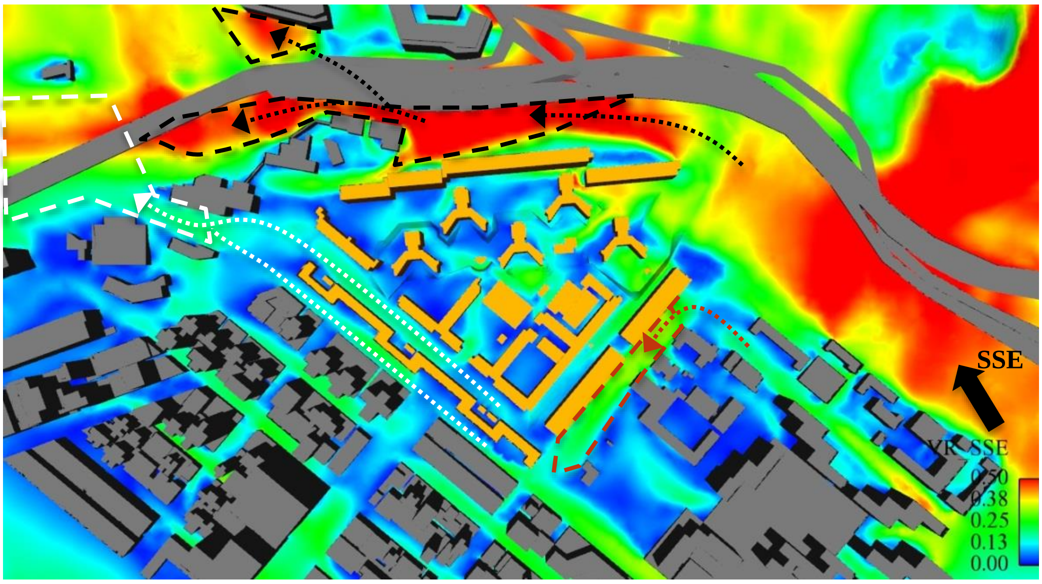

Figure 33 VR Contour Plot under SSE wind direction for Baseline Scheme

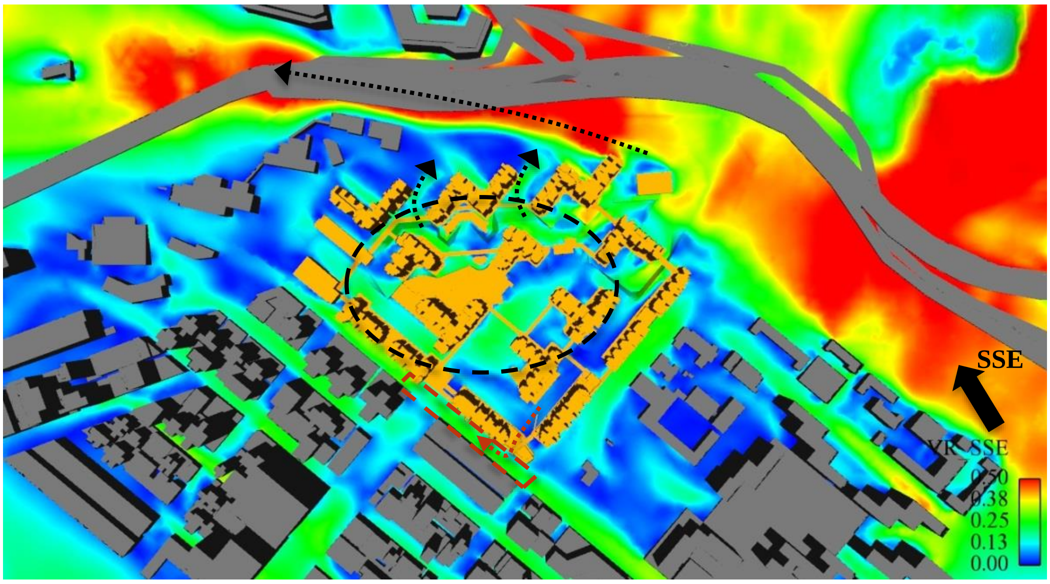

Figure 34 VR Contour Plot under SSE wind direction for Proposed Scheme

4.2.8 Southerly Wind

Baseline Scheme

Under the S wind condition, the hilly open area behind the north continuous building blocks (**black dotted lines** in Figure 35) is more ventilated than that in the Proposed Scheme as the prevailing wind is squeezed by the linear building blocks (**black arrow**).

Meanwhile, the west / southwest continuous building blocks on Po On Road capture the south prevailing wind from Hing Wah Street and downwash it to the pedestrian level, leading to a more ventilated environment on Hing Wah Street (**brown dotted lines**).

Proposed Scheme

On the contrary, the view corridor created along Hing Wah Street for the Proposed Development directs the prevailing wind to the inner area of the Estate (**white circle** in Figure 36), particularly through the empty bays on the G/F and the podium of Block 11B (**white arrow**).

Further north to the Development, some of the prevailing wind passes through the separations of Blocks 1 to 3, merges with another stream of incoming wind along Ching Cheung Road Highway (**black arrows**) and shift the flow further northwest. As a result, the frontage area of Villa Carlton (**black dotted lines**) is better in ventilation than that in the Baseline.

The section of Cheung Fat Street adjacent to the Development (**brown dotted lines**) is more ventilated in this scenario as a result of taller building heights of Blocks 13 and 14 which are able to capture and downwash the prevailing wind to the local pedestrian level.

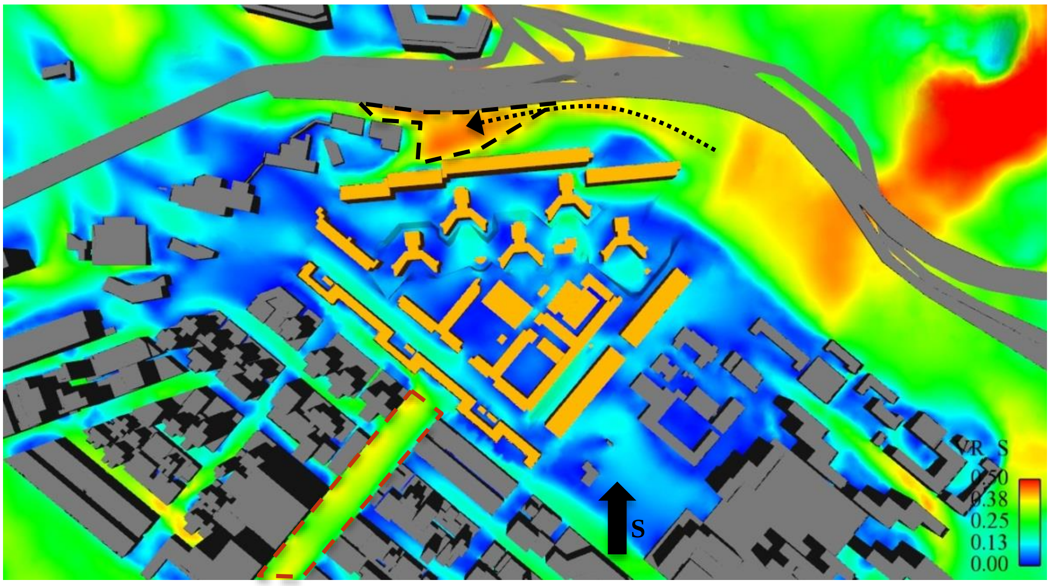

Figure 35 VR Contour Plot under S wind direction for Baseline Scheme

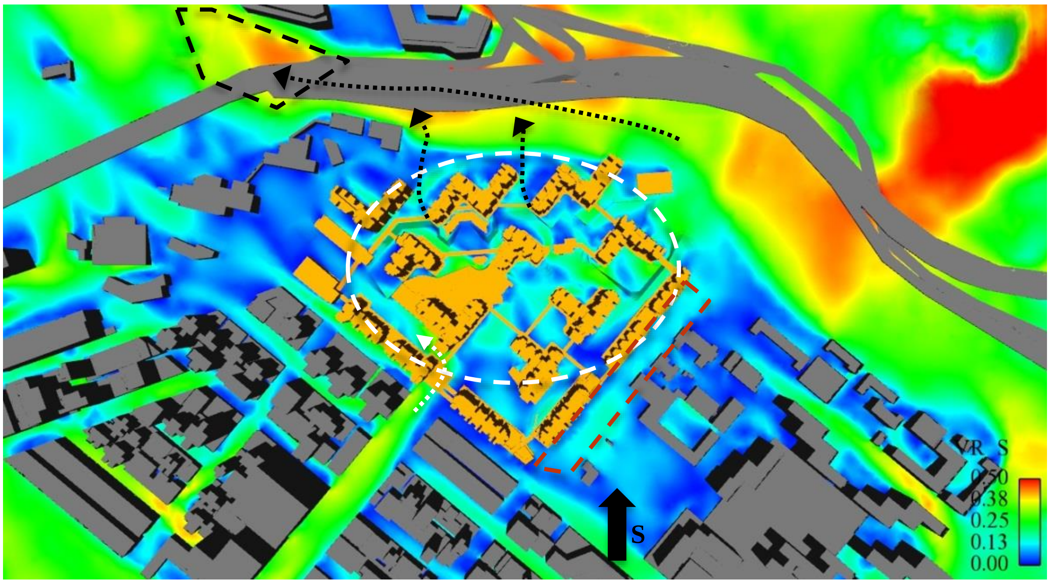

Figure 36 VR Contour Plot under S wind direction for Proposed Scheme

4.3 SVR and LVR

The average wind velocity ratios (VR) of all test points were extracted from the CFD simulation and are now presented in tables in Appendix A. According to the Technical Circular as briefed in Section 3.4.4, the VR at each test point should be assessed while the Site Spatial-average Velocity Ratio (SVR) and the Local Spatial-average Velocity Ratio (LVR) considering the pre-dominant prevailing winds need to be derived to assess the overall impact of the Proposed Development on the neighbouring wind environment. The SVR and LVR values are summarized as follows,

Table 6 SVR and LVR table

	Baseline Scheme	Proposed Scheme
SVR	0.19	0.20
LVR	0.21	0.22

The results indicate slightly higher SVR and LVR values are found in the Proposed Scheme within the Assessment Area as defined by the Technical Circular, meaning that the overall wind performance at pedestrian level is marginally better in the Proposed Scheme.

4.4 Focus Areas

Focus areas with frequent pedestrian access and activity zones within the required 1H belt of the Assessment Area are defined for further analysis, as shown in Figure 37 and Figure 16. The VR of all 12 focus areas (FA) are summarised in Table 7.

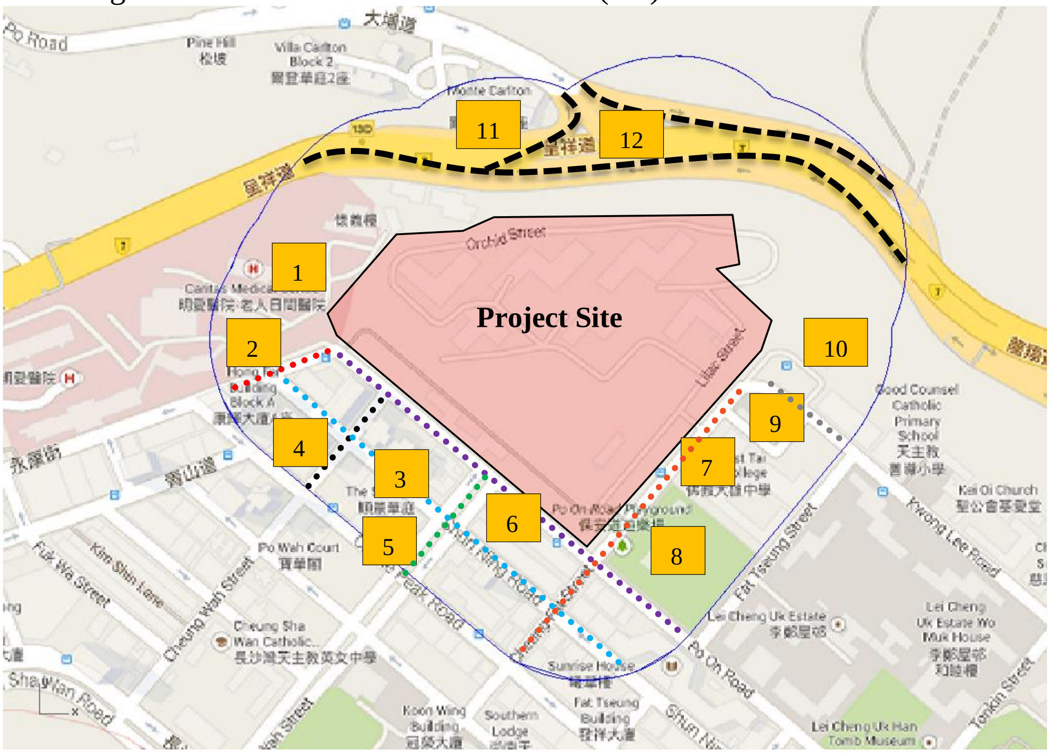

Figure 37 Focus Areas Location

Table 7 Average VR Results at Focus Areas

No.	Focus Area	Test Points	Baseline Scheme Average VR	Proposed Scheme Average VR
1	**Caritas Medical Center**	O1-O11, P20-P25	0.16	0.14
2	**Wing Hong Street**	O12-O14	0.11	0.10
3	**Shun Ning Road**	O15-O16, O18, O20-O21, O23, O25-O26, O28, O30-O31	0.15	0.20
4	**Cheung Wah Street**	O17-O19	0.14	0.10
5	**Hing Wah Street**	O22-O24	0.14	0.19
6	**Po On Road**	P10-P19, O32-O33	0.16	0.21
7	**Cheung Fat Street**	P2-P10, O27-O29	0.19	0.20
8	**Po On Road Playground**	O34-O39	0.11	0.15
9	**Cheung Sha Wan Jockey Club Clinic & Kwong Lee Road**	O40-O43	0.17	0.18
10	**So Uk Bus Terminal**	P1, O44-O45	0.21	0.20
11	**Monte Carlton**	O65-O66	0.25	0.24
12	**Ching Cheung Road Highway**	O46-O64	0.40	0.39

There are 6 focus areas better in overall wind performance in each of the studied schemes.

Baseline Scheme

In the Baseline scenario, the continuous building blocks at the north (facing Ching Cheung Road Highway), southwest (on Po On Road) and southeast (on Cheung Fat Street) end of the original Estate direct or downwash most of the wind to the local pedestrian level, accelerating the airflow there. As a result, **FA1, FA11** and **FA12** (due north), **FA2** and **FA4** (due west/southwest) and **FA10** (due east) respectively benefit from this building feature.

Proposed Scheme

In the Proposed Scheme, the view corridor (major local air path for NE/NNE wind) of the Proposed Development stretching to Hing Wah Street favours more ventilation to and fro along **FA5**.

Likewise the creation of empty bays on G/F and/or at podium level of Blocks 11 and 12 as described in Figure 8 and Section 5.3 makes three of the local air paths primarily for NE/NNE wind possible and improves the wind condition of the adjacent streets in the downwind region, i.e. **FA3** and **FA6**.

FA7 and the open space of **FA8** benefit from the stepping profile of building heights shaped by Blocks 9 and 14 and their taller building heights, which capture more high-altitude wind, downwash it to the pedestrian level and direct it towards the area through the separation between Blocks 13 and 14.

There is a little increase in VR at **FA9** where the taller building height of Block 14 captures more high-altitude wind and downwash it to the local pedestrian level.

5. Wind Enhancement Features

In order to enhance the ventilation performance of the surrounding areas, the Proposed Scheme adopted few wind enhancement features, such as

- Wide building separations from 10m to more than 32m
- Stepping profile of building height
- Local air paths
- Empty bays on G/F and at podium levels

5.1 Stepping Profile of Building Height

The Proposed Scheme has adopted a strategy of stepping building height profile to help capture the wind from the high level and downwash it to the low level. This complies with the recommendation in the "Urban Design Guidehline", in which a decreasing height of buildings towards the direction of the prevailing wind is preferable. Figure 39 to Figure 41 show how the stepping profile (amongst Blocks 8, 9, 13, 14A and 14B) in the Development captures the high-level wind to the pedestrian level using the downwash effect.

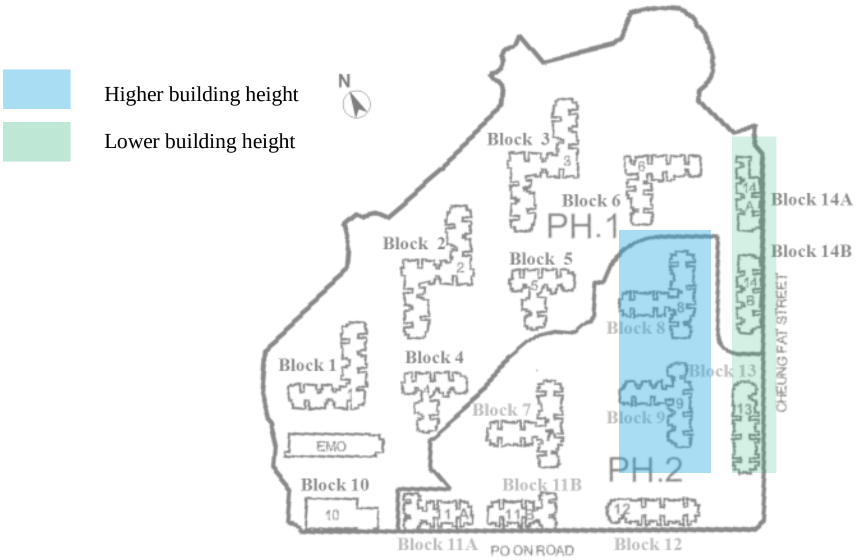

Figure 38 Strategy of stepping building height profile for So Uk Estate

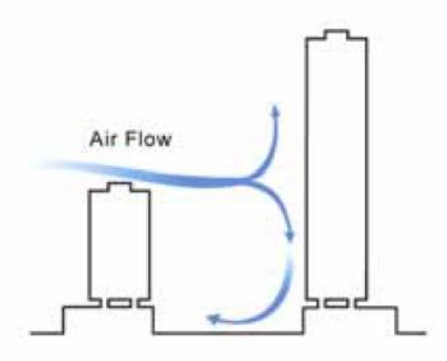

Figure 39 Concept of stepping height profile to divert winds to lower levels (*Source: Urban Design Guideline, Chapter 11*)

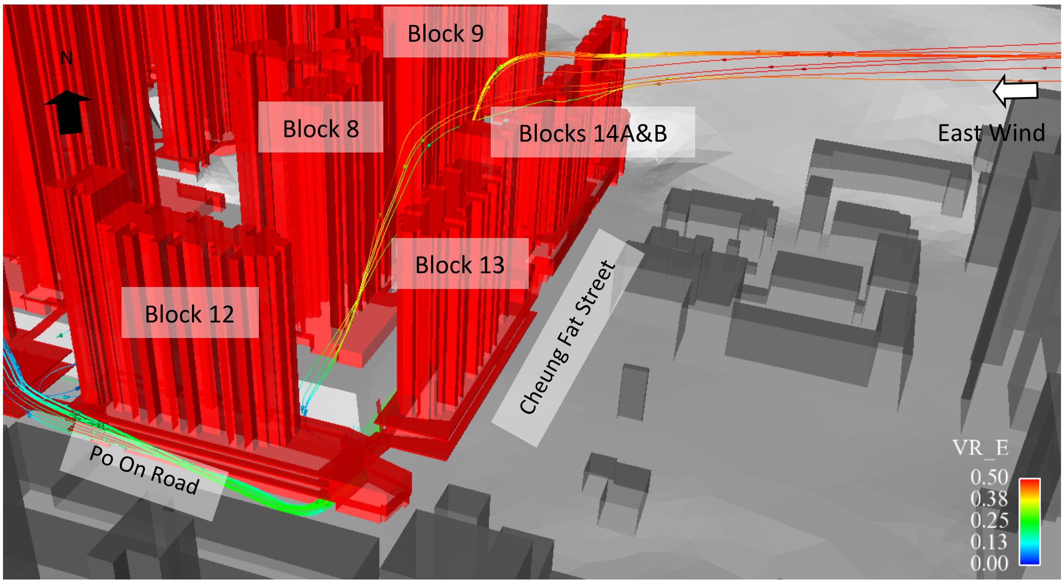

Figure 40 Streamline plot of downwash effect of Blk. 8 & 9 on Po On Rd under E wind

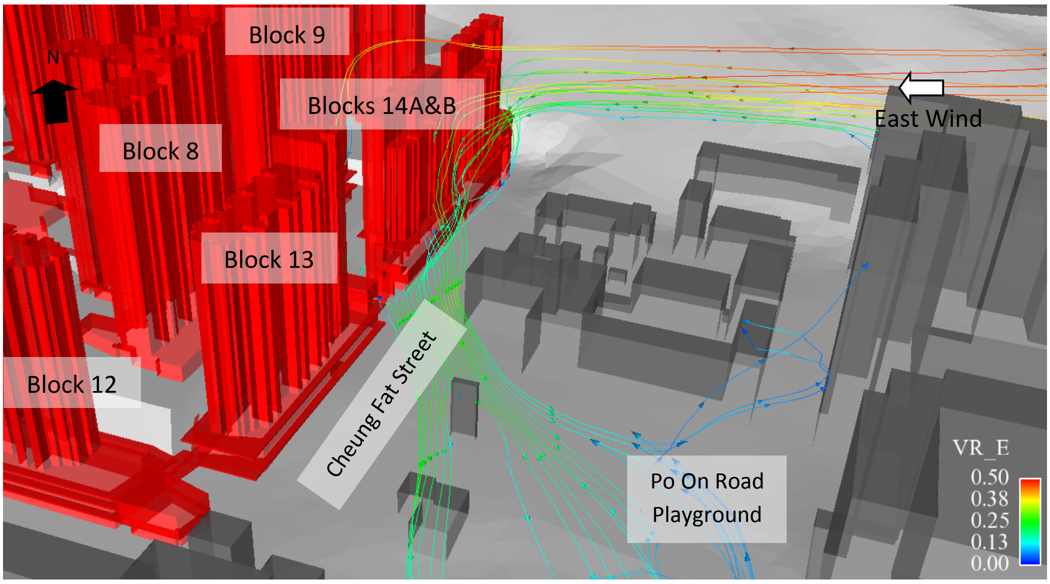

Figure 41 Streamline plot of downwash effect of Blk. 14A&B on Cheung Fat Street and Po On Road Playground under E wind

5.2 Local Air Paths

As stated in the "Urban Design Guidelines" developed by Planning Department, "An array of main streets/wide main avenues should be aligned in parallel, or up to 30 degree to the prevailing wind direction, in order to maximize the penetration of prevailing wind through the district". Therefore, the building orientation, separation and disposition of the Proposed Scheme shall be carefully arranged and shall create at least two local air paths for prevailing winds.

As briefed in Section 2.2.2 and shown in Figure 39, under NE/NNE prevailing wind conditions, one local air path connected to Hing Wah Street, which is also the view corridor of the region, provides mountain breeze to the Cheung Sha Wan District (**green arrow** in Figure 42). Three other local air paths for NE/NNE prevailing wind are provided by the Development to enhance the wind environment on Hing Wah Road and Po On Road (**violet arrows**).

Two local air paths are created for E/ENE prevailing wind (**blue arrows**). The local air paths in the Proposed Scheme can help deliver the prevailing wind beyond the Development and improve the wind condition of the surroundings.

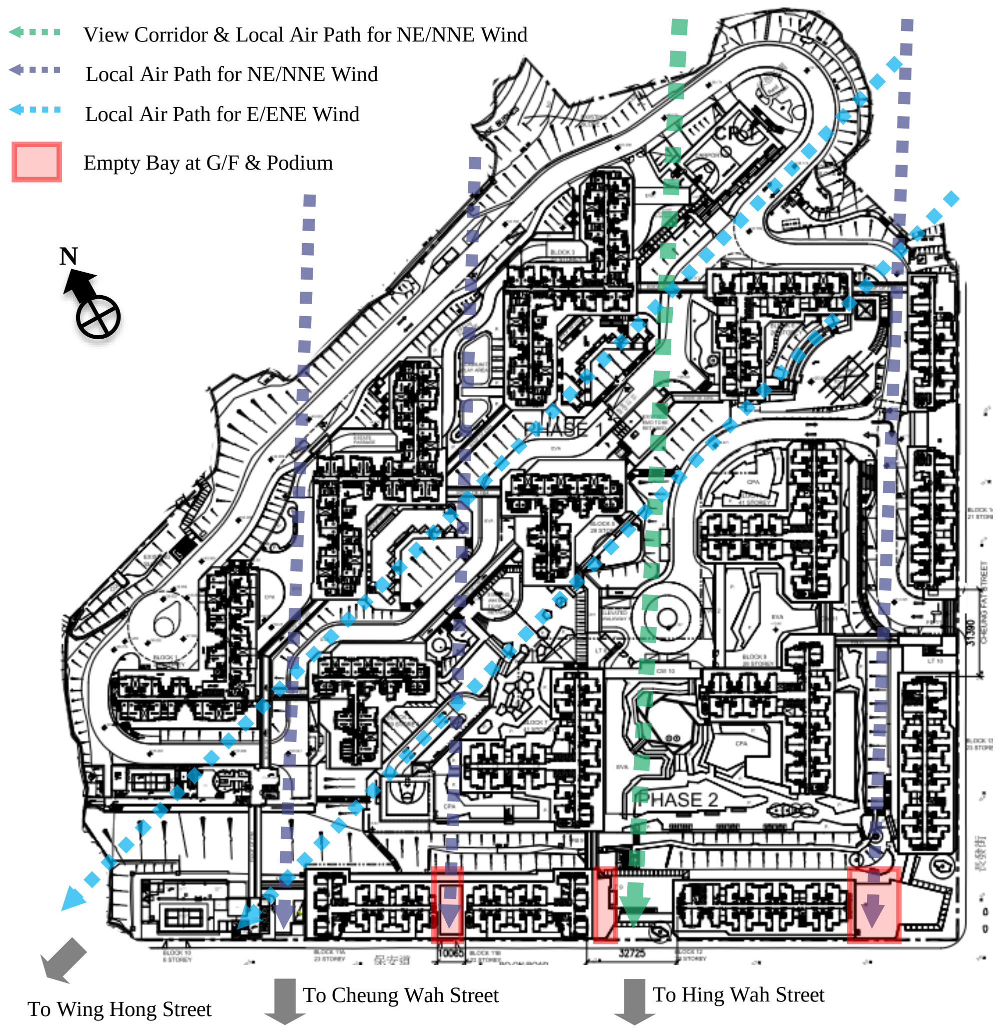

Figure 42 Building layout of the Proposed Scheme

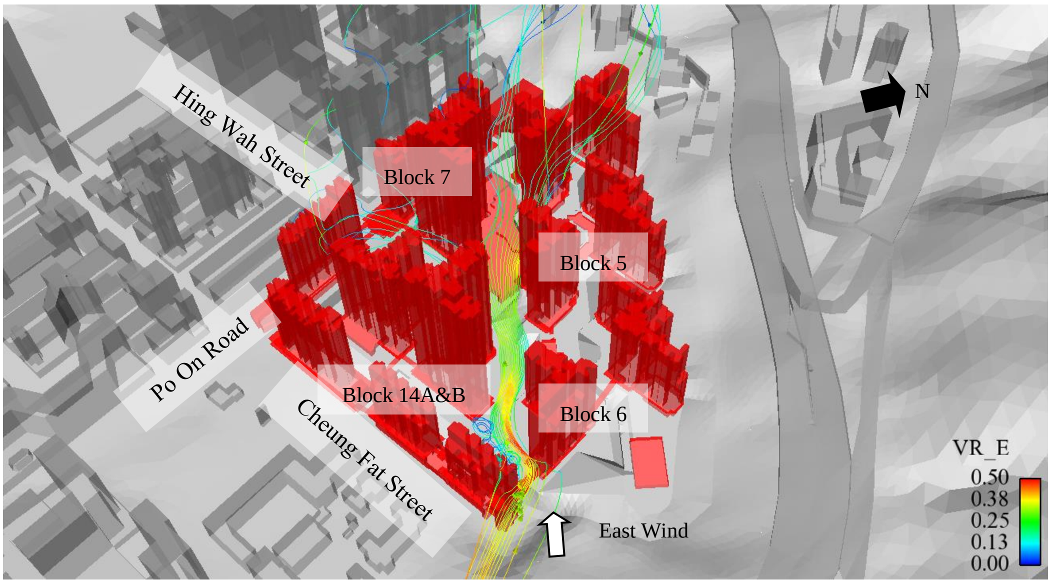

Figure 43 Local air paths under E wind

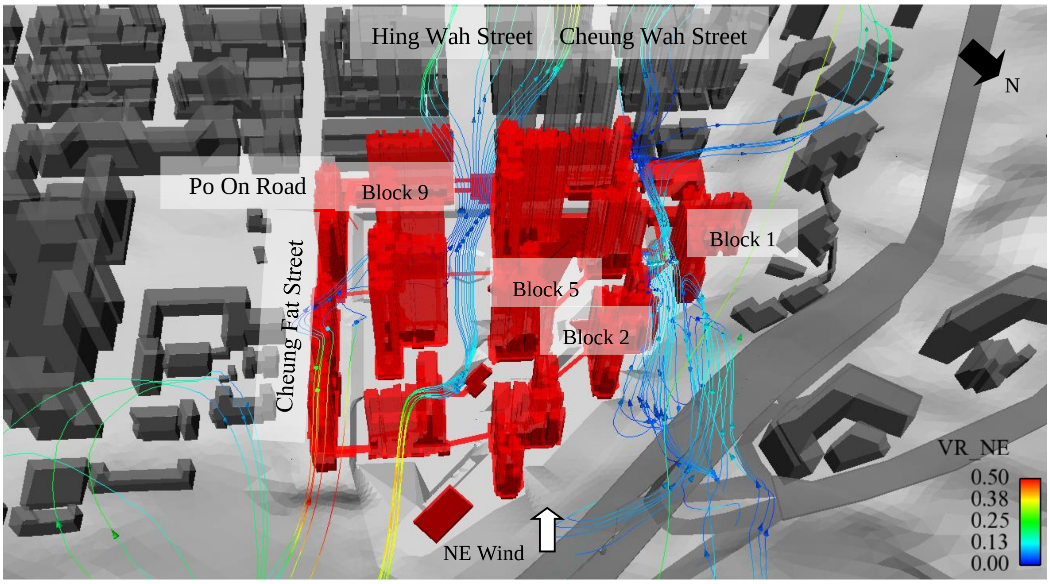

Figure 44 Local air paths under NE Wind

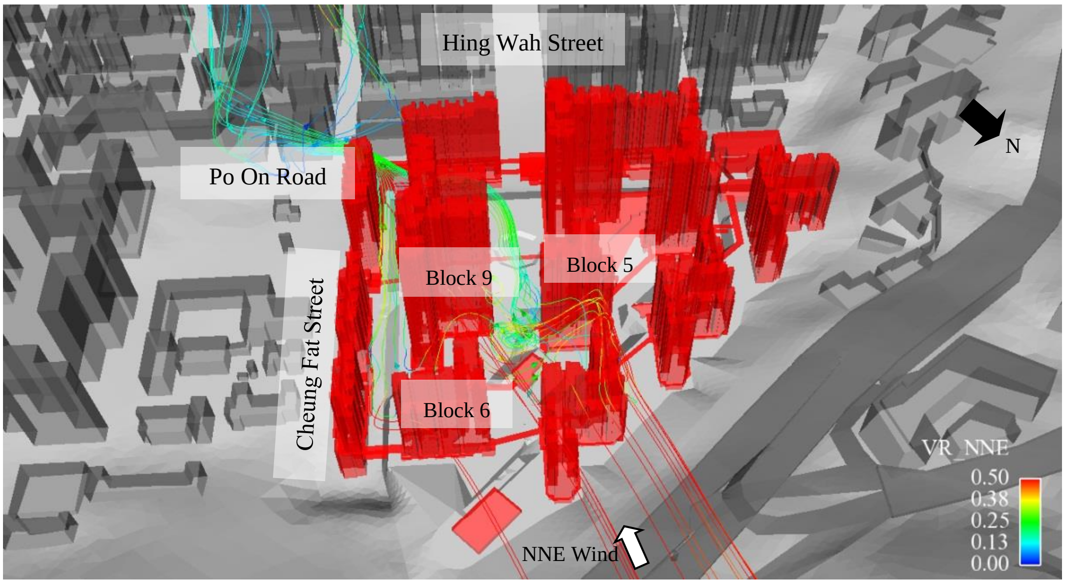

Figure 45 Local air paths under NNE Wind

5.3 Empty Bays

As indicated by elevation drawings in Figure 46 and Figure 47 and vector streamline plots in Figure 48 to Figure 50 below, the design of empty bays in the Proposed Scheme enhances the wind permeability of the Development by diverting the prevailing wind towards Po On Road and beyond. Without this feature, two of the local air paths identified for NE/NNE wind would not exist. This also reflects the difference in VR of the adjacent roads between the Proposed Scheme and the Baseline Scheme.

Figure 46 Empty bays of Blocks 11A & 11B on G/F and at podium level

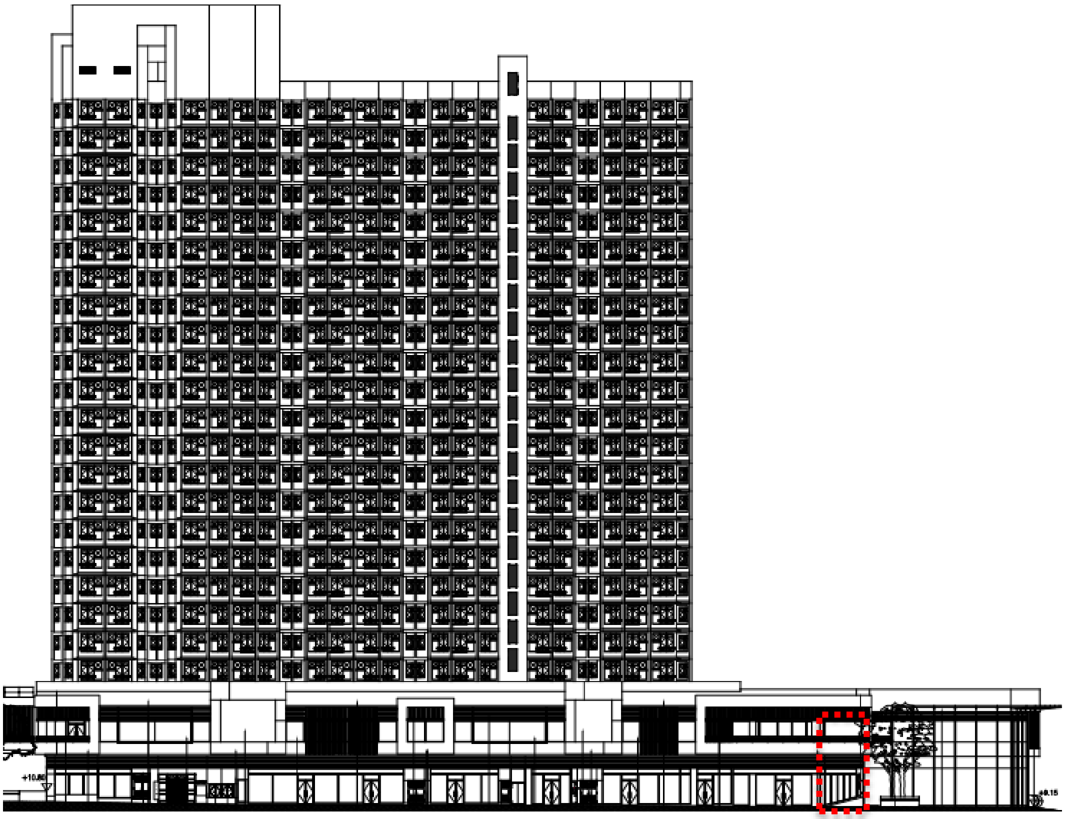

Figure 47 Empty bays of Block 12 on G/F and at podium level

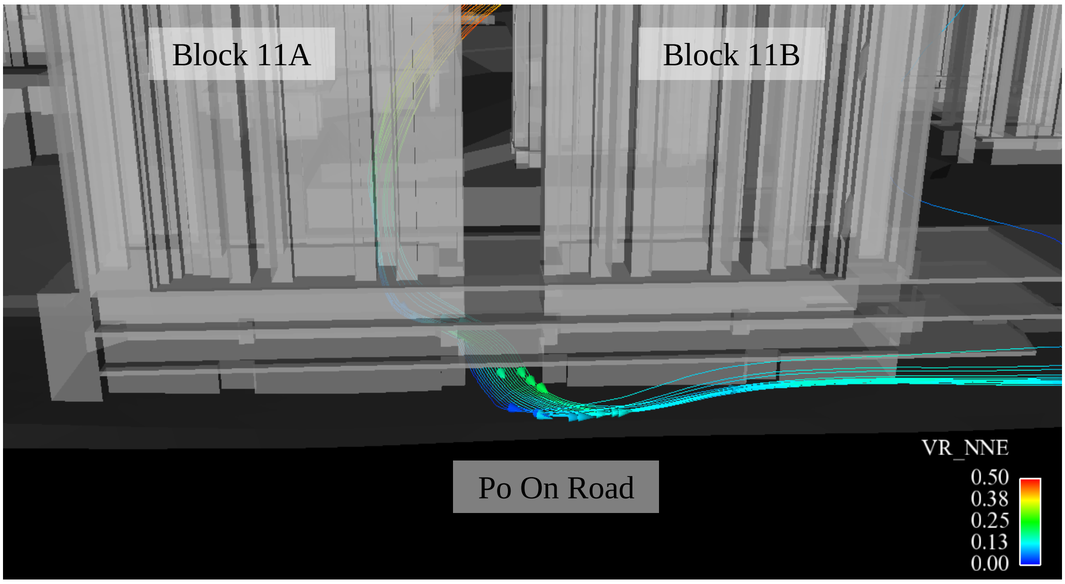

Figure 48 Empty bays of Blocks 11A&11B to enhance NNE wind on Po On Road

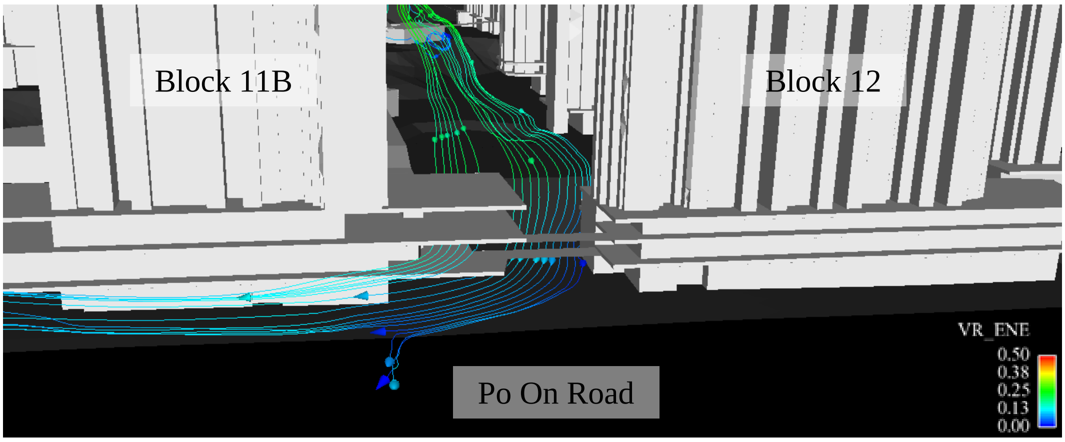

Figure 49 Empty bays of Block 11B to enhance ENE wind on Po On Road

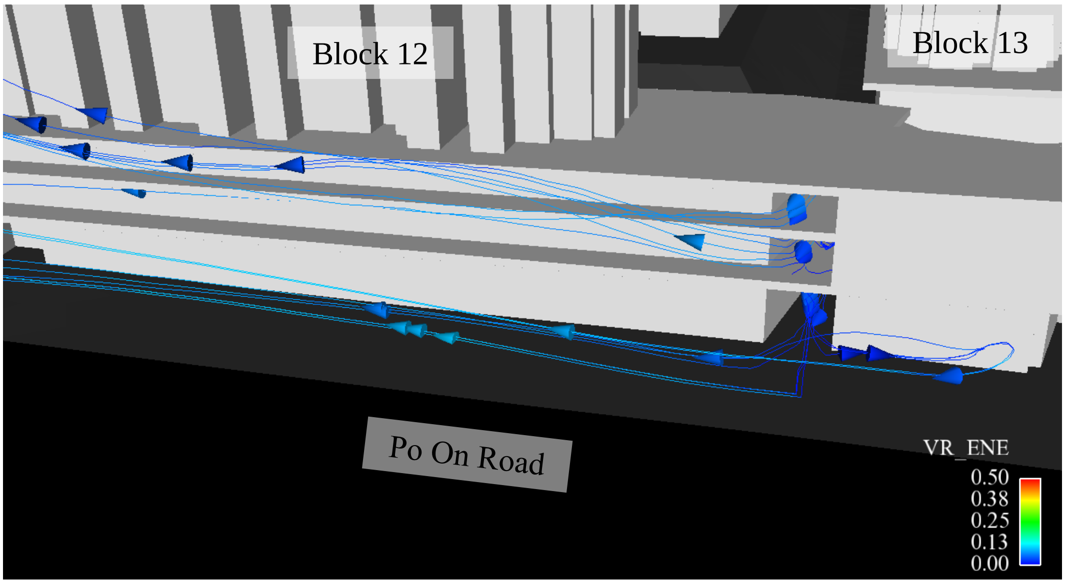

Figure 50 Empty bays of Block 12 to enhance ENE wind on Po On Road

6. Conclusion

An Air Ventilation Assessment (AVA) was conducted for the proposed Re-development of So Uk Estate to analyse the wind environment surrounding the project site before and after the Development.

A series of CFD simulations using Realizable k- εturbulence model were performed based on the standard methodology for the Initial Study as stipulated in the Technical Circular and Technical Guide. Eight wind directions (NNE, NE, ENE, E, ESE, SE, SSE and S) were considered, which altogether represented 78.2% of annual wind availability. The ventilation performance for the Development at the site boundary and the focus areas of surroundings was assessed.

According to the Technical Circular, the Velocity Ratio (VR) at each test point was derived in forms of SVR and LVR. A total of 35 perimeter test points and 66 overall test points were located to evaluate the ventilation.

The ventilation performance of the Development is concluded as follows,

- Slightly higher LVR (0.22) and SVR (0.20) are found in Proposed Schemes than those in Baseline Scheme (0.21 in LVR and 0.19 in SVR).
- The Proposed Scheme achieves higher VRs than the Baseline Scheme in 6 focus areas: Shun Ning Road (FA3), Hing Wah Street (FA5), Po On Road (FA6), Cheung Fat Street (FA7), Po On Road Playground (FA8) and Cheung Sha Wan Jockey Club Clinic & Kwong Lee Road (FA9).
- On the other hand, the Baseline Scheme has higher VRs in 6 other areas: Caritas Medical Centre (FA1), Wing Hong Street (FA2), Cheung Wah Street (FA4), So Uk Bus Terminal (FA10), Monte Carlton (FA11) and Ching Cheung Road Highway (FA12).

To minimise the ventilation impacts or to enhance the ventilation performance of the surroundings, the Proposed Scheme has adopted the following design features:

- Six local air paths (incl. the view corridor) primarily for NE/NNE and E/ENE prevailing wind directions,
- Stepping profile of building height to utilise downwash effect, and
- Empty bays on G/F and at podium level.

Appendix A

VR Result Tables

A1 VR Table of Baseline Scheme

Table 8 VR of Perimeter Test Points in Baseline Scheme

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	Overall
Frequency	0.08	0.11	0.18	0.16	0.09	0.06	0.06	0.05	0.78
P1	0.12	0.10	0.03	0.15	0.17	0.06	0.11	0.11	0.10
P2	0.16	0.11	0.23	0.14	0.18	0.21	0.24	0.12	0.17
P3	0.18	0.09	0.22	0.12	0.21	0.32	0.34	0.10	0.19
P4	0.22	0.06	0.27	0.17	0.19	0.33	0.33	0.10	0.20
P5	0.18	0.03	0.31	0.22	0.20	0.36	0.32	0.10	0.22
P6	0.21	0.02	0.31	0.24	0.18	0.34	0.28	0.05	0.22
P7	0.26	0.02	0.30	0.24	0.17	0.33	0.25	0.11	0.22
P8	0.25	0.04	0.32	0.24	0.17	0.27	0.20	0.12	0.21
P9	0.17	0.01	0.28	0.23	0.10	0.09	0.15	0.07	0.16
P10	0.08	0.05	0.29	0.21	0.18	0.29	0.22	0.16	0.19
P11	0.18	0.11	0.20	0.10	0.15	0.29	0.10	0.10	0.15
P12	0.21	0.11	0.22	0.10	0.15	0.21	0.08	0.07	0.15
P13	0.29	0.12	0.17	0.07	0.18	0.24	0.12	0.10	0.15
P14	0.35	0.17	0.04	0.05	0.16	0.17	0.07	0.29	0.13
P15	0.33	0.13	0.06	0.08	0.20	0.24	0.20	0.09	0.14
P16	0.22	0.18	0.04	0.08	0.19	0.26	0.22	0.17	0.14
P17	0.25	0.25	0.07	0.07	0.16	0.22	0.17	0.12	0.15
P18	0.22	0.31	0.13	0.12	0.17	0.19	0.16	0.03	0.17
P19	0.13	0.30	0.13	0.13	0.17	0.15	0.14	0.00	0.15
P20	0.10	0.27	0.13	0.12	0.13	0.09	0.08	0.06	0.13
P21	0.09	0.10	0.06	0.02	0.10	0.16	0.14	0.09	0.08
P22	0.47	0.09	0.20	0.17	0.11	0.12	0.18	0.03	0.18
P23	0.49	0.08	0.05	0.13	0.10	0.01	0.06	0.07	0.12
P24	0.48	0.05	0.12	0.16	0.17	0.16	0.13	0.08	0.16
P25	0.33	0.10	0.25	0.35	0.37	0.42	0.47	0.36	0.31
P26	0.17	0.12	0.30	0.36	0.40	0.46	0.47	0.40	0.32
P27	0.25	0.00	0.29	0.21	0.30	0.34	0.34	0.32	0.24

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	Overall
Frequency	**0.08**	**0.11**	**0.18**	**0.16**	**0.09**	**0.06**	**0.06**	**0.05**	**0.78**
P28	0.23	0.02	0.29	0.11	0.21	0.20	0.22	0.24	0.19
P29	0.26	0.11	0.33	0.10	0.24	0.12	0.20	0.20	0.20
P30	0.21	0.10	0.34	0.13	0.44	0.44	0.51	0.07	0.27
P31	0.29	0.05	0.29	0.27	0.40	0.47	0.49	0.24	0.29
P32	0.20	0.09	0.19	0.25	0.24	0.29	0.36	0.34	0.23
P33	0.28	0.10	0.24	0.10	0.07	0.16	0.24	0.29	0.17
P34	0.10	0.08	0.18	0.15	0.16	0.22	0.25	0.26	0.16
P35	0.10	0.12	0.26	0.21	0.19	0.10	0.22	0.06	0.18

Table 9 VR of Overall Test Points in Baseline Scheme

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	Overall
Frequency	0.08	0.12	0.18	0.16	0.09	0.06	0.06	0.05	0.80
O1	0.46	0.29	0.37	0.33	0.36	0.46	0.49	0.10	0.36
O2	0.38	0.07	0.16	0.09	0.11	0.10	0.09	0.12	0.14
O3	0.32	0.08	0.05	0.09	0.20	0.23	0.28	0.05	0.14
O4	0.19	0.07	0.19	0.15	0.21	0.32	0.27	0.03	0.17
O5	0.03	0.05	0.15	0.10	0.10	0.10	0.16	0.05	0.10
O6	0.34	0.06	0.09	0.09	0.03	0.09	0.05	0.06	0.10
O7	0.13	0.23	0.11	0.07	0.10	0.09	0.12	0.10	0.12
O8	0.09	0.28	0.15	0.11	0.11	0.13	0.10	0.08	0.14
O9	0.16	0.24	0.13	0.15	0.16	0.23	0.19	0.15	0.17
O10	0.10	0.14	0.19	0.15	0.14	0.15	0.15	0.03	0.14
O11	0.17	0.14	0.18	0.16	0.18	0.14	0.15	0.08	0.16
O12	0.02	0.02	0.05	0.06	0.08	0.04	0.07	0.04	0.05
O13	0.14	0.20	0.13	0.09	0.11	0.10	0.11	0.14	0.13
O14	0.13	0.15	0.18	0.15	0.14	0.17	0.16	0.11	0.16
O15	0.14	0.20	0.11	0.10	0.08	0.15	0.08	0.16	0.12
O16	0.13	0.15	0.07	0.07	0.08	0.19	0.12	0.19	0.11
O17	0.05	0.25	0.09	0.11	0.10	0.05	0.08	0.09	0.11
O18	0.17	0.23	0.13	0.11	0.17	0.26	0.21	0.18	0.17
O19	0.09	0.30	0.15	0.14	0.15	0.07	0.08	0.13	0.15
O20	0.16	0.16	0.10	0.13	0.19	0.27	0.21	0.19	0.16
O21	0.09	0.08	0.16	0.12	0.19	0.22	0.19	0.25	0.15
O22	0.24	0.16	0.04	0.05	0.07	0.12	0.14	0.33	0.11
O23	0.17	0.22	0.13	0.05	0.16	0.20	0.13	0.33	0.15
O24	0.25	0.16	0.18	0.05	0.07	0.07	0.11	0.35	0.14
O25	0.23	0.20	0.18	0.10	0.17	0.26	0.17	0.10	0.17
O26	0.37	0.10	0.10	0.07	0.19	0.27	0.23	0.16	0.16
O27	0.20	0.06	0.18	0.17	0.08	0.08	0.10	0.06	0.13
O28	0.33	0.10	0.15	0.13	0.19	0.27	0.21	0.15	0.18
O29	0.21	0.11	0.18	0.13	0.04	0.09	0.07	0.11	0.13
O30	0.21	0.05	0.08	0.05	0.22	0.32	0.25	0.19	0.14

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	Overall
Frequency	0.08	0.12	0.18	0.16	0.09	0.06	0.06	0.05	0.80
O31	0.20	0.12	0.12	0.04	0.23	0.35	0.25	0.22	0.16
O32	0.17	0.11	0.21	0.06	0.17	0.34	0.24	0.19	0.17
O33	0.22	0.16	0.41	0.14	0.20	0.40	0.31	0.24	0.26
O34	0.17	0.03	0.27	0.15	0.05	0.03	0.15	0.02	0.13
O35	0.25	0.09	0.15	0.07	0.07	0.04	0.02	0.07	0.10
O36	0.25	0.09	0.19	0.03	0.10	0.09	0.15	0.10	0.13
O37	0.25	0.04	0.28	0.16	0.15	0.11	0.09	0.14	0.17
O38	0.15	0.05	0.05	0.03	0.05	0.08	0.09	0.05	0.06
O39	0.03	0.03	0.09	0.05	0.04	0.03	0.04	0.01	0.05
O40	0.08	0.03	0.19	0.11	0.13	0.10	0.07	0.06	0.11
O41	0.17	0.03	0.25	0.13	0.16	0.11	0.09	0.08	0.14
O42	0.09	0.05	0.38	0.24	0.09	0.14	0.09	0.08	0.18
O43	0.24	0.04	0.44	0.29	0.18	0.08	0.17	0.02	0.23
O44	0.32	0.10	0.33	0.20	0.27	0.32	0.35	0.29	0.26
O45	0.46	0.09	0.30	0.21	0.22	0.23	0.30	0.25	0.25
O46	0.33	0.19	0.55	0.58	0.46	0.42	0.49	0.43	0.45
O47	0.47	0.14	0.22	0.38	0.41	0.40	0.38	0.27	0.32
O48	0.60	0.26	0.51	0.55	0.47	0.41	0.42	0.43	0.47
O49	0.52	0.22	0.32	0.37	0.47	0.43	0.39	0.28	0.37
O50	0.84	0.32	0.35	0.50	0.45	0.39	0.37	0.31	0.44
O51	0.52	0.30	0.38	0.47	0.49	0.45	0.25	0.36	0.41
O52	0.52	0.34	0.41	0.55	0.48	0.41	0.46	0.26	0.44
O53	0.40	0.35	0.45	0.55	0.56	0.53	0.42	0.25	0.46
O54	0.69	0.36	0.40	0.42	0.42	0.45	0.47	0.23	0.43
O55	0.35	0.26	0.39	0.53	0.58	0.54	0.47	0.21	0.42
O56	0.21	0.31	0.40	0.41	0.42	0.51	0.51	0.35	0.39
O57	0.27	0.09	0.39	0.51	0.60	0.55	0.56	0.30	0.40
O58	0.43	0.27	0.27	0.55	0.56	0.47	0.52	0.32	0.41
O59	0.50	0.19	0.38	0.46	0.50	0.47	0.48	0.24	0.40
O60	0.36	0.28	0.17	0.22	0.33	0.42	0.49	0.34	0.29
O61	0.16	0.25	0.26	0.43	0.47	0.39	0.38	0.28	0.33

Baseline	NNE	NE	ENE	E	ESE	SE	SSE	S	Overall
Frequency	**0.08**	**0.12**	**0.18**	**0.16**	**0.09**	**0.06**	**0.06**	**0.05**	**0.80**
O62	0.55	0.46	0.21	0.38	0.44	0.44	0.39	0.35	0.38
O63	0.62	0.41	0.39	0.43	0.43	0.41	0.37	0.29	0.42
O64	0.46	0.34	0.30	0.34	0.33	0.36	0.29	0.09	0.32
O65	0.23	0.05	0.01	0.26	0.23	0.14	0.21	0.05	0.15
O66	0.39	0.42	0.31	0.29	0.39	0.37	0.40	0.42	0.36

A2 VR Table of Proposed Scheme

Table 10 VR of Perimeter Test Points in Proposed Scheme

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	Overall
Frequency	0.08	0.11	0.18	0.16	0.09	0.06	0.06	0.05	0.78
P1	0.63	0.13	0.04	0.14	0.08	0.05	0.10	0.14	0.15
P2	0.28	0.14	0.24	0.13	0.08	0.18	0.20	0.13	0.18
P3	0.28	0.05	0.21	0.18	0.12	0.30	0.28	0.11	0.19
P4	0.09	0.10	0.24	0.20	0.15	0.32	0.26	0.12	0.19
P5	0.03	0.12	0.33	0.24	0.19	0.36	0.25	0.12	0.22
P6	0.08	0.10	0.28	0.28	0.27	0.36	0.22	0.14	0.23
P7	0.10	0.09	0.26	0.15	0.12	0.33	0.18	0.14	0.18
P8	0.11	0.13	0.29	0.25	0.24	0.26	0.11	0.13	0.21
P9	0.38	0.11	0.27	0.26	0.24	0.22	0.08	0.10	0.23
P10	0.46	0.14	0.26	0.25	0.23	0.29	0.27	0.15	0.26
P11	0.45	0.25	0.35	0.24	0.17	0.27	0.24	0.05	0.27
P12	0.38	0.32	0.41	0.31	0.24	0.33	0.25	0.02	0.31
P13	0.25	0.30	0.39	0.27	0.20	0.32	0.26	0.04	0.28
P14	0.13	0.24	0.31	0.14	0.15	0.14	0.22	0.27	0.21
P15	0.18	0.19	0.19	0.04	0.16	0.16	0.29	0.07	0.15
P16	0.08	0.17	0.19	0.09	0.16	0.21	0.32	0.19	0.16
P17	0.14	0.13	0.18	0.10	0.16	0.20	0.29	0.20	0.16
P18	0.14	0.15	0.14	0.03	0.12	0.18	0.26	0.22	0.13
P19	0.06	0.12	0.09	0.06	0.10	0.13	0.17	0.18	0.10
P20	0.05	0.11	0.10	0.04	0.09	0.08	0.08	0.13	0.08
P21	0.23	0.15	0.10	0.25	0.29	0.18	0.12	0.08	0.18
P22	0.33	0.05	0.18	0.06	0.02	0.02	0.12	0.07	0.11
P23	0.34	0.03	0.03	0.06	0.02	0.02	0.05	0.08	0.07
P24	0.35	0.05	0.08	0.09	0.05	0.06	0.08	0.10	0.10
P25	0.15	0.10	0.31	0.02	0.02	0.04	0.03	0.07	0.12
P26	0.20	0.11	0.26	0.21	0.18	0.18	0.16	0.02	0.18
P27	0.13	0.08	0.22	0.03	0.02	0.06	0.01	0.20	0.10
P28	0.21	0.22	0.29	0.18	0.14	0.20	0.13	0.27	0.21

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	Overall
Frequency	0.08	0.11	0.18	0.16	0.09	0.06	0.06	0.05	0.78
P29	0.46	0.06	0.39	0.40	0.41	0.39	0.52	0.33	0.36
P30	0.45	0.14	0.41	0.40	0.41	0.46	0.53	0.32	0.38
P31	0.37	0.20	0.27	0.26	0.28	0.36	0.41	0.26	0.29
P32	0.26	0.16	0.20	0.24	0.20	0.23	0.36	0.35	0.23
P33	0.20	0.05	0.27	0.19	0.17	0.22	0.33	0.33	0.21
P34	0.43	0.24	0.18	0.19	0.23	0.25	0.33	0.20	0.24
P35	0.54	0.25	0.21	0.12	0.05	0.04	0.10	0.14	0.19

Table 11 VR of Overall Test Points in Proposed Scheme

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	Overall
Frequency	0.08	0.11	0.18	0.16	0.09	0.06	0.06	0.05	0.78
O1	0.63	0.37	0.42	0.36	0.32	0.22	0.19	0.18	0.36
O2	0.28	0.04	0.17	0.03	0.04	0.03	0.08	0.08	0.10
O3	0.28	0.02	0.05	0.07	0.06	0.05	0.11	0.05	0.08
O4	0.09	0.17	0.23	0.22	0.23	0.14	0.11	0.04	0.18
O5	0.03	0.07	0.22	0.14	0.15	0.11	0.09	0.07	0.13
O6	0.08	0.08	0.18	0.19	0.23	0.13	0.05	0.07	0.14
O7	0.10	0.11	0.09	0.18	0.25	0.12	0.05	0.03	0.12
O8	0.11	0.11	0.09	0.08	0.10	0.05	0.07	0.12	0.09
O9	0.38	0.05	0.14	0.03	0.13	0.04	0.13	0.14	0.12
O10	0.46	0.11	0.15	0.07	0.09	0.25	0.17	0.03	0.16
O11	0.45	0.11	0.16	0.11	0.06	0.23	0.12	0.08	0.16
O12	0.38	0.02	0.04	0.04	0.02	0.04	0.05	0.04	0.07
O13	0.25	0.13	0.11	0.11	0.12	0.25	0.18	0.12	0.14
O14	0.13	0.05	0.16	0.06	0.07	0.06	0.14	0.06	0.10
O15	0.18	0.13	0.05	0.15	0.14	0.31	0.22	0.15	0.15
O16	0.08	0.16	0.13	0.19	0.15	0.34	0.25	0.19	0.17
O17	0.14	0.01	0.01	0.01	0.04	0.06	0.06	0.07	0.04
O18	0.14	0.18	0.18	0.20	0.18	0.36	0.26	0.19	0.20
O19	0.06	0.07	0.07	0.06	0.06	0.10	0.09	0.13	0.07
O20	0.05	0.18	0.18	0.19	0.16	0.37	0.26	0.21	0.19
O21	0.23	0.23	0.23	0.17	0.11	0.35	0.22	0.20	0.21
O22	0.33	0.02	0.07	0.13	0.06	0.20	0.17	0.20	0.13
O23	0.34	0.29	0.33	0.14	0.23	0.31	0.16	0.30	0.26
O24	0.35	0.22	0.20	0.15	0.03	0.07	0.14	0.34	0.18
O25	0.15	0.23	0.30	0.17	0.26	0.34	0.15	0.14	0.23
O26	0.20	0.08	0.07	0.15	0.22	0.35	0.16	0.19	0.16
O27	0.13	0.15	0.21	0.30	0.13	0.13	0.12	0.06	0.18
O28	0.21	0.32	0.13	0.24	0.21	0.31	0.20	0.17	0.22
O29	0.46	0.34	0.15	0.20	0.03	0.11	0.07	0.11	0.19
O30	0.45	0.07	0.10	0.10	0.27	0.38	0.25	0.22	0.19

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	Overall
Frequency	0.08	0.11	0.18	0.16	0.09	0.06	0.06	0.05	0.78
O31	0.37	0.10	0.08	0.09	0.28	0.40	0.25	0.24	0.19
O32	0.26	0.11	0.14	0.19	0.07	0.33	0.25	0.17	0.17
O33	0.20	0.20	0.42	0.11	0.17	0.42	0.31	0.23	0.26
O34	0.43	0.12	0.23	0.26	0.24	0.22	0.09	0.10	0.22
O35	0.54	0.10	0.18	0.16	0.08	0.13	0.05	0.09	0.17
O36	-	0.17	0.20	0.13	0.06	0.11	0.14	0.11	0.13
O37	NNE	0.11	0.20	0.25	0.20	0.32	0.16	0.17	0.18
O38	0.08	0.14	0.06	0.04	0.06	0.09	0.08	0.11	0.08
O39	0.63	0.02	0.13	0.04	0.04	0.06	0.01	0.09	0.12
O40	0.28	0.05	0.23	0.18	0.06	0.12	0.09	0.05	0.15
O41	0.28	0.15	0.20	0.16	0.21	0.23	0.04	0.13	0.18
O42	0.09	0.10	0.36	0.16	0.09	0.17	0.10	0.04	0.17
O43	0.03	0.08	0.44	0.28	0.06	0.07	0.18	0.10	0.20
O44	0.08	0.21	0.31	0.16	0.20	0.33	0.37	0.28	0.23
O45	0.10	0.20	0.27	0.17	0.13	0.22	0.30	0.19	0.20
O46	0.11	0.23	0.53	0.62	0.48	0.45	0.52	0.48	0.45
O47	0.38	0.23	0.33	0.41	0.45	0.43	0.41	0.30	0.36
O48	0.46	0.28	0.63	0.58	0.51	0.42	0.45	0.47	0.50
O49	0.45	0.24	0.30	0.20	0.50	0.46	0.42	0.33	0.33
O50	0.38	0.31	0.30	0.54	0.47	0.40	0.41	0.36	0.40
O51	0.25	0.29	0.40	0.35	0.51	0.45	0.26	0.40	0.37
O52	0.13	0.35	0.40	0.41	0.46	0.46	0.52	0.32	0.38
O53	0.18	0.34	0.47	0.50	0.59	0.56	0.47	0.30	0.44
O54	0.08	0.37	0.43	0.40	0.43	0.44	0.48	0.38	0.38
O55	0.14	0.26	0.41	0.51	0.63	0.59	0.54	0.30	0.42
O56	0.14	0.32	0.43	0.42	0.49	0.47	0.51	0.31	0.39
O57	0.06	0.08	0.42	0.52	0.64	0.61	0.63	0.42	0.41
O58	0.05	0.28	0.28	0.54	0.58	0.59	0.63	0.41	0.40
O59	0.23	0.17	0.43	0.43	0.50	0.49	0.50	0.26	0.38
O60	0.33	0.31	0.22	0.31	0.22	0.27	0.30	0.31	0.28
O61	0.34	0.30	0.31	0.45	0.47	0.45	0.50	0.26	0.38

Proposed	NNE	NE	ENE	E	ESE	SE	SSE	S	Overall
Frequency	**0.08**	**0.11**	**0.18**	**0.16**	**0.09**	**0.06**	**0.06**	**0.05**	**0.78**
O62	0.35	0.46	0.36	0.46	0.38	0.36	0.35	0.30	0.39
O63	0.15	0.44	0.48	0.48	0.38	0.37	0.34	0.27	0.40
O64	0.20	0.37	0.36	0.37	0.29	0.30	0.27	0.05	0.31
O65	0.13	0.06	0.02	0.28	0.22	0.18	0.10	0.05	0.13
O66	0.21	0.44	0.34	0.29	0.34	0.38	0.42	0.45	0.35

Appendix B

Directional VR Contour Plots

B1 Directional Contour Plots for Baseline Scheme

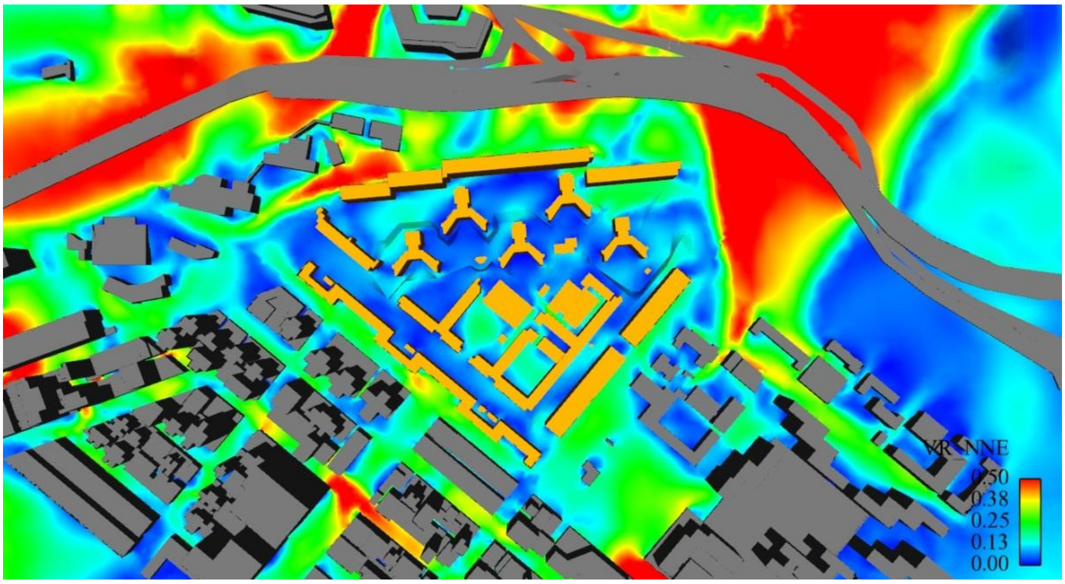

Figure 51 Contour Plot under NNE Direction (Baseline Scheme)

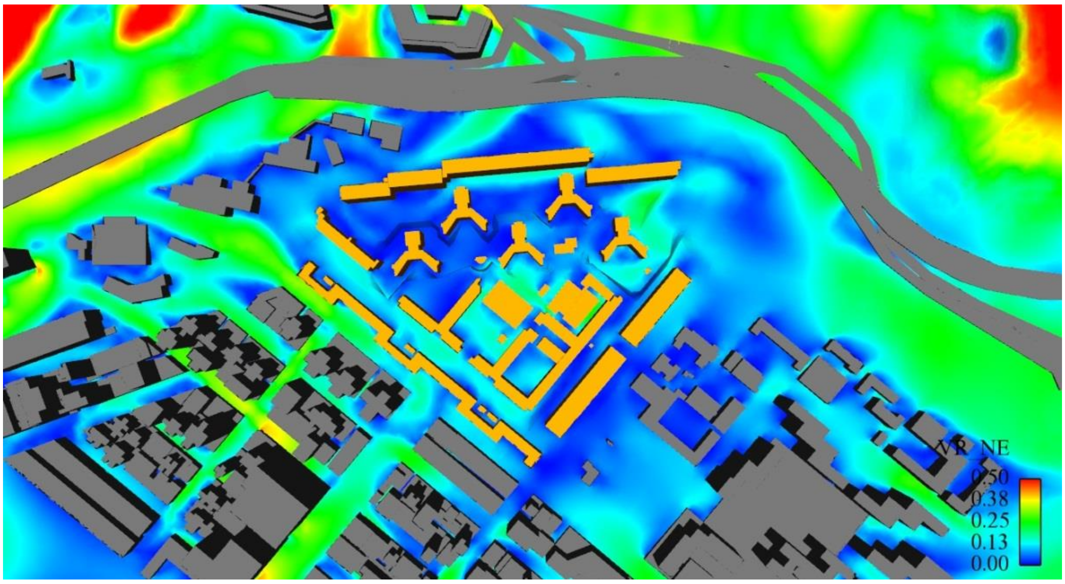

Figure 52 Contour Plot under NE Direction (Baseline Scheme)

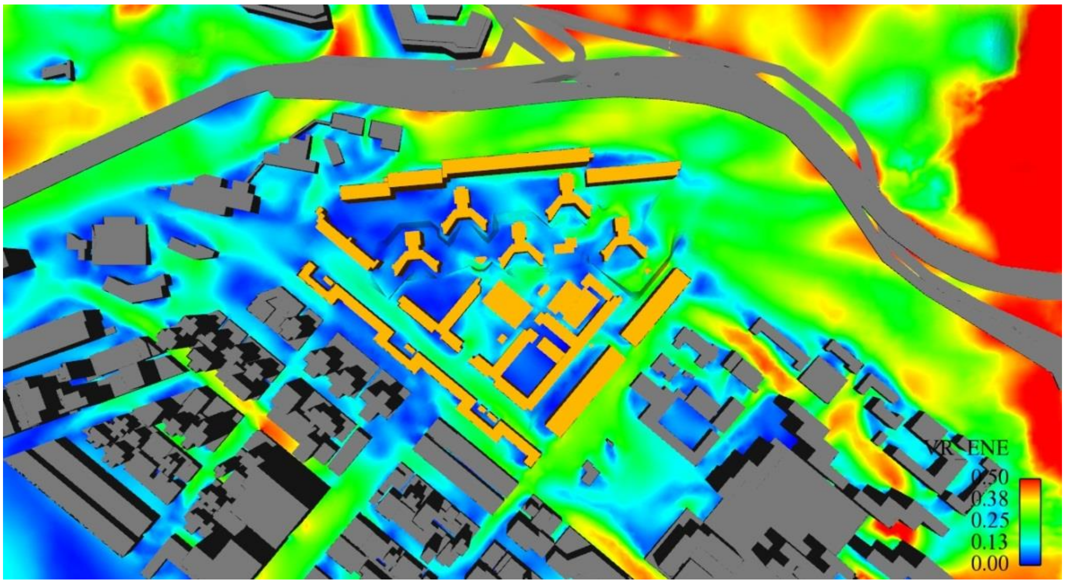

Figure 53 Contour Plot under ENE Direction (Baseline Scheme)

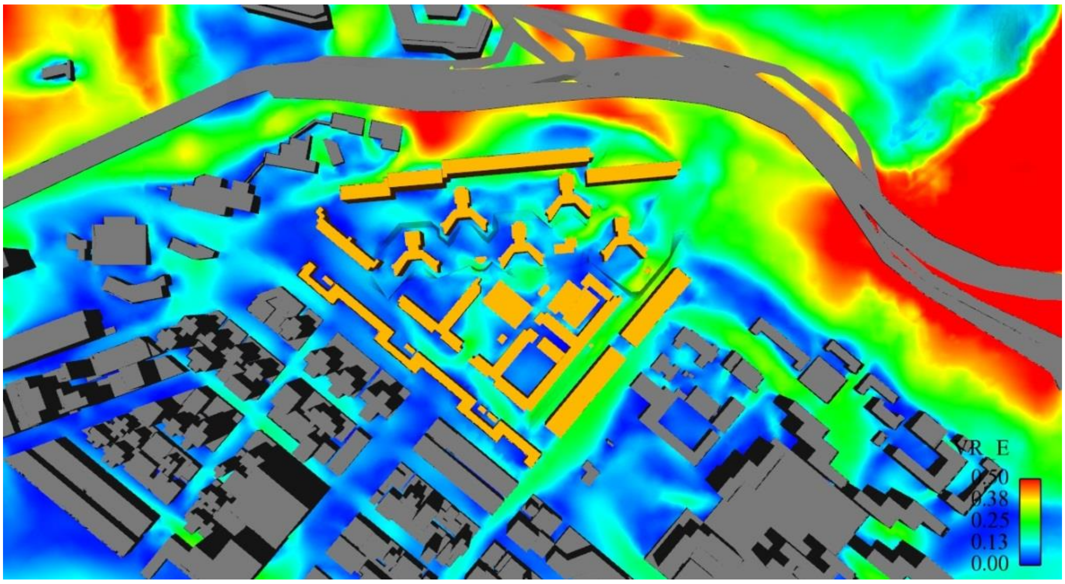

Figure 54 Contour Plot under E Direction (Baseline Scheme)

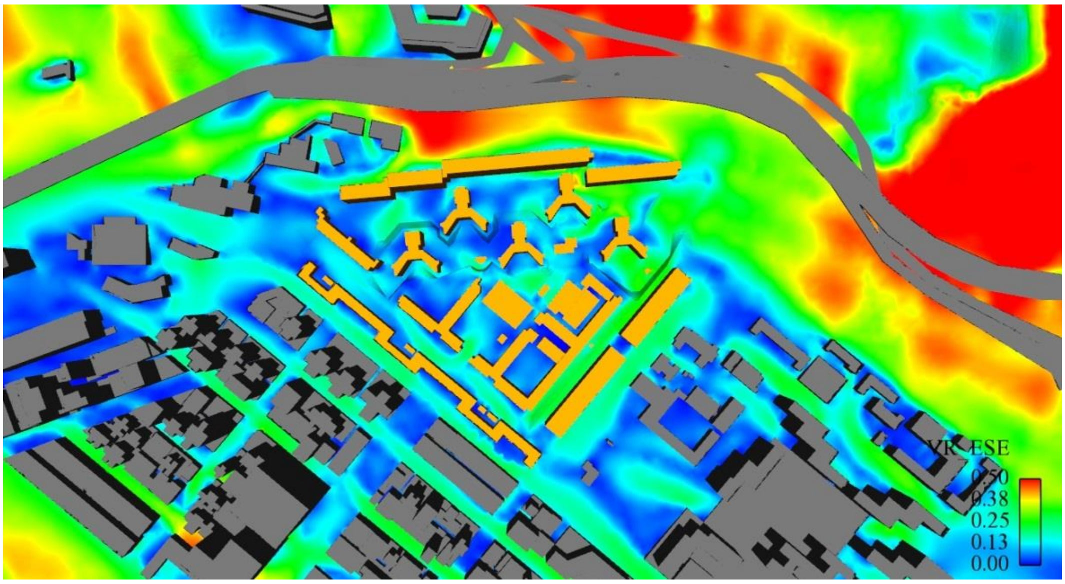

Figure 55 Contour Plot under ESE Direction (Baseline Scheme)

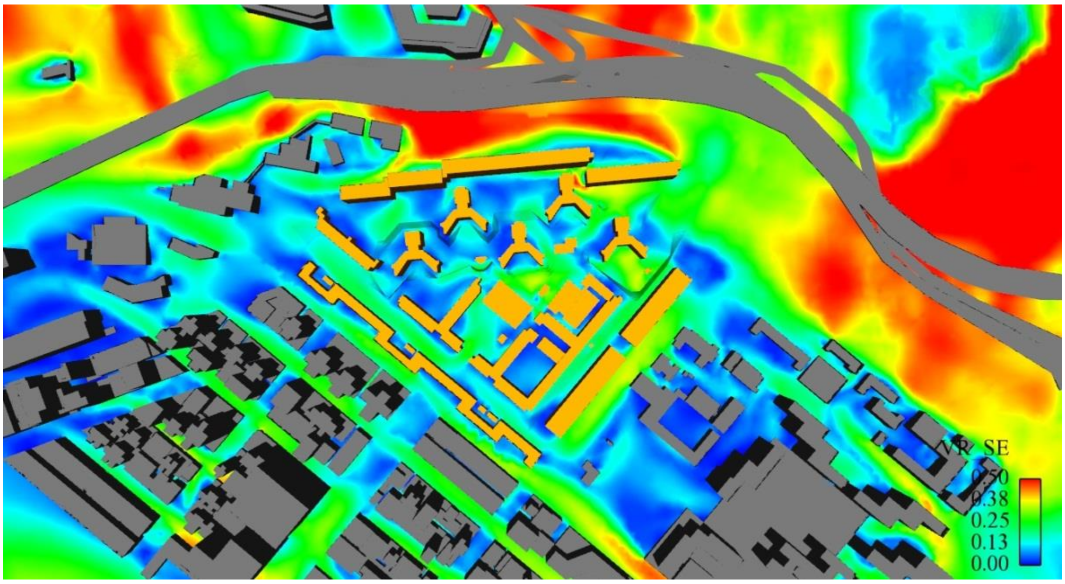

Figure 56 Contour Plot under SE Direction (Baseline Scheme)

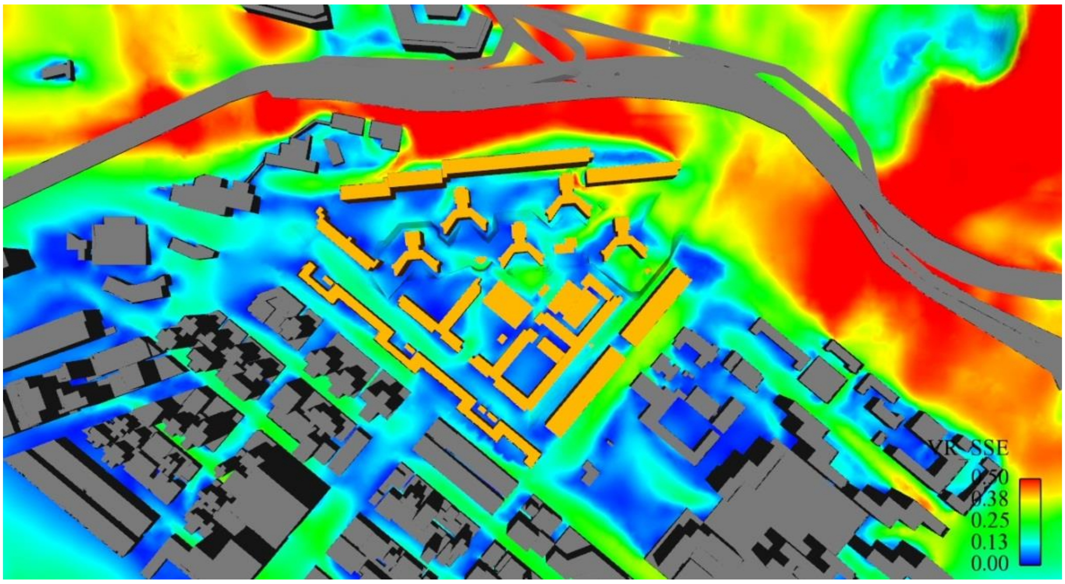

Figure 57 Contour Plot under SSE Direction (Baseline Scheme)

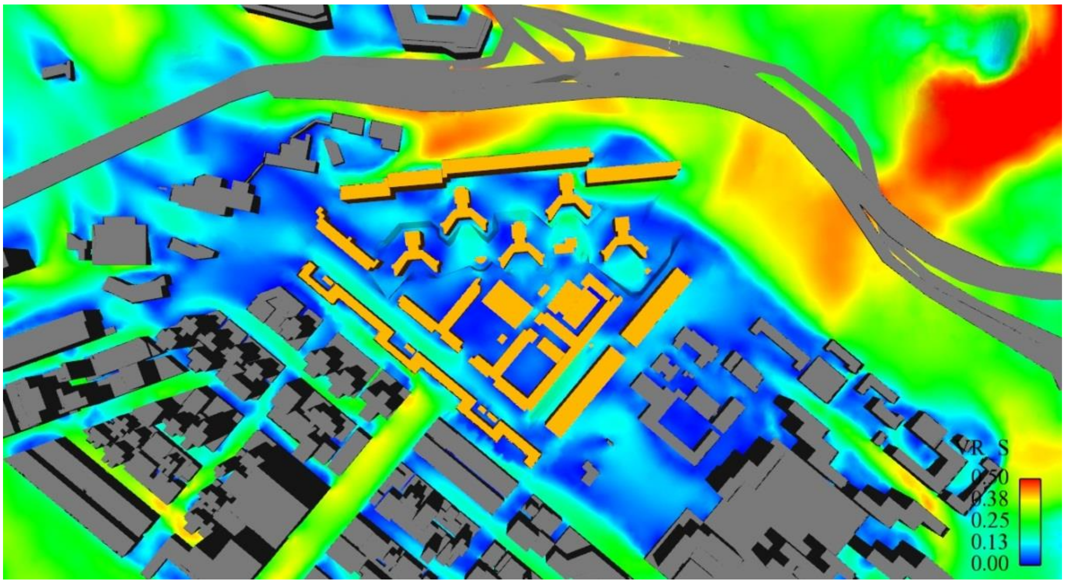

Figure 58 Contour Plot under S Direction (Baseline Scheme)

B2 Directional VR Contour Plots for Proposed Scheme

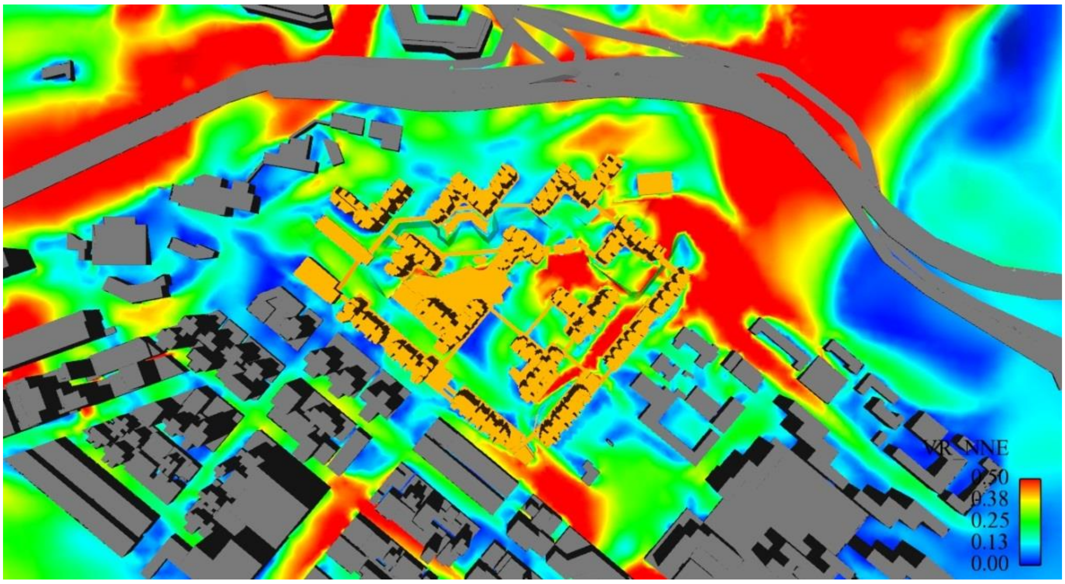

Figure 59 Contour Plot under NNE Direction (Proposed Scheme)

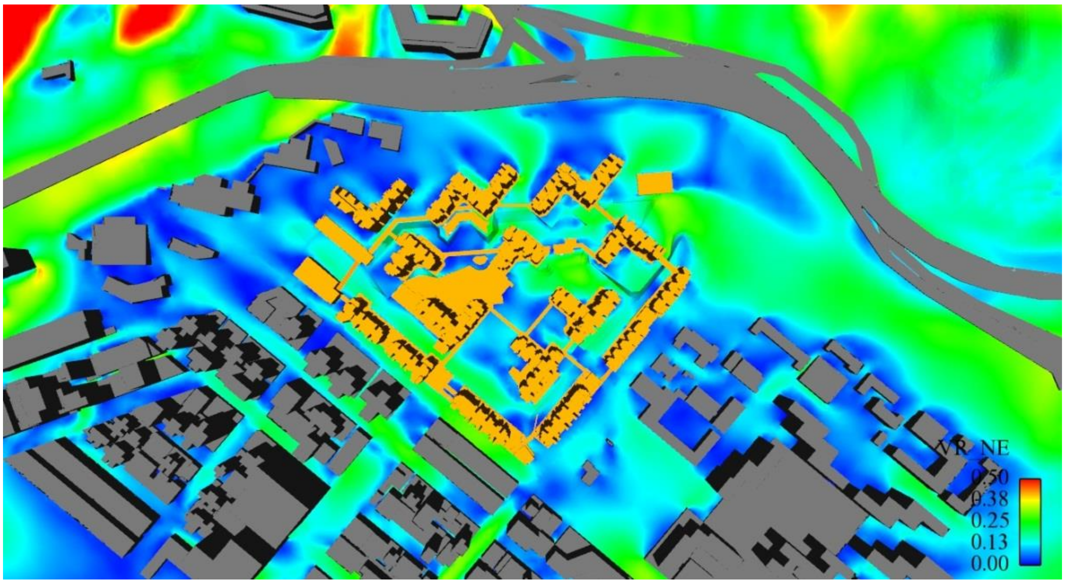

Figure 60 Contour Plot under NE Direction (Proposed Scheme)

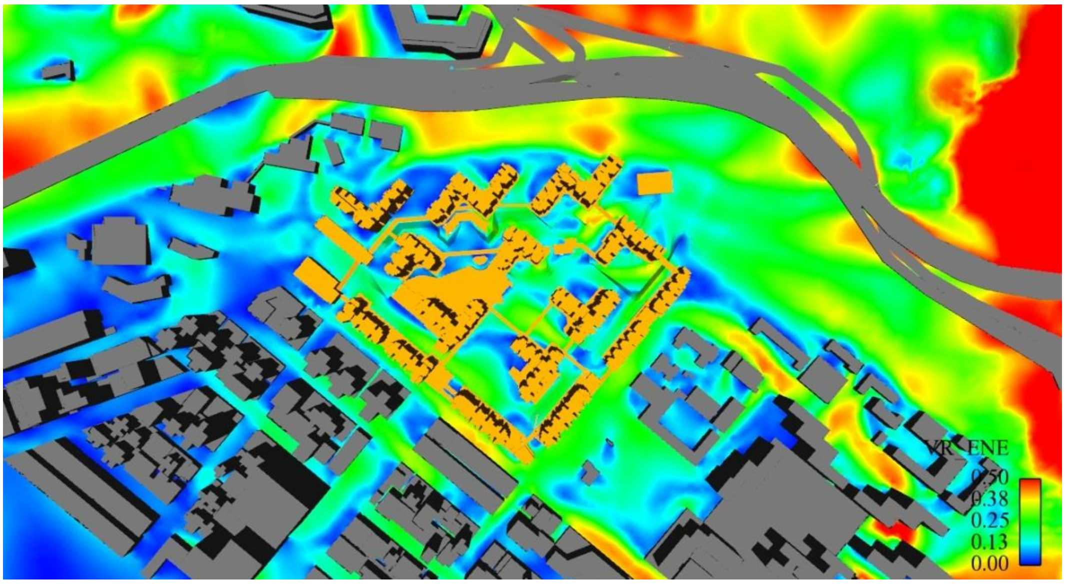

Figure 61 Contour Plot under ENE Direction (Proposed Scheme)

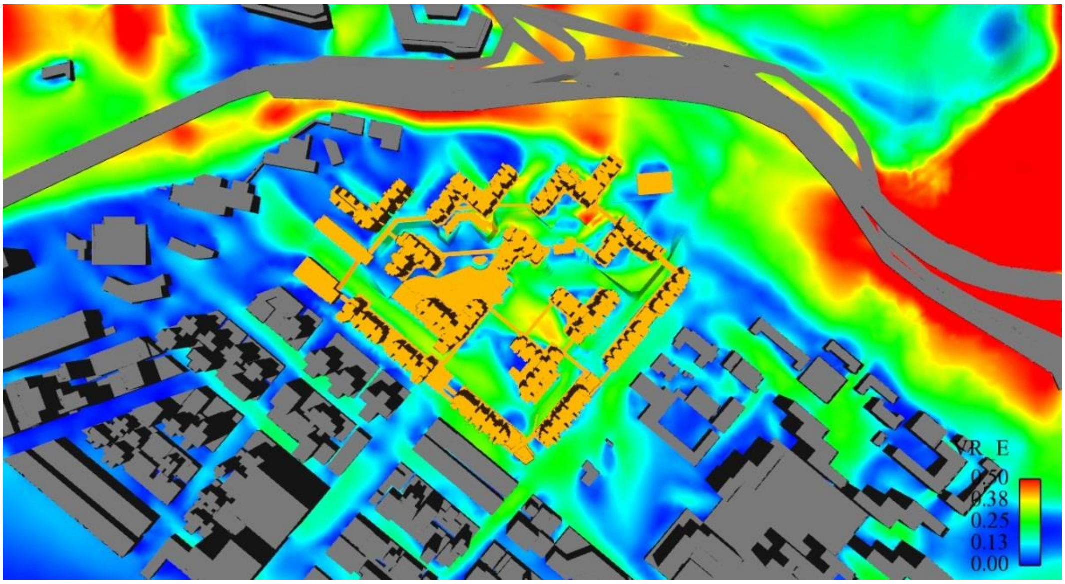

Figure 62 E Contour Plot under E Direction (Proposed Scheme)

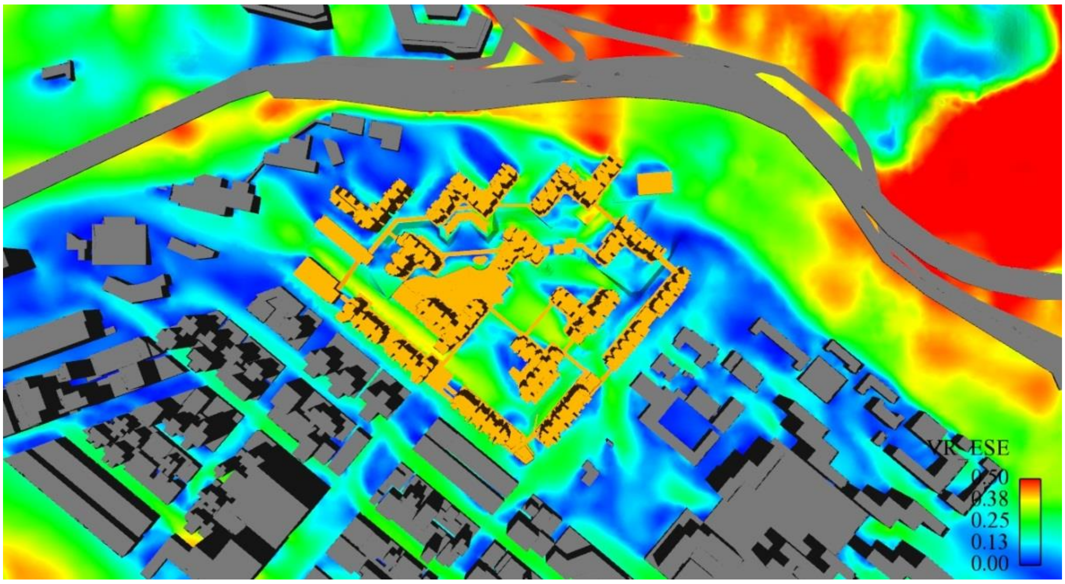

Figure 63 Contour Plot under ESE Direction (Proposed Scheme)

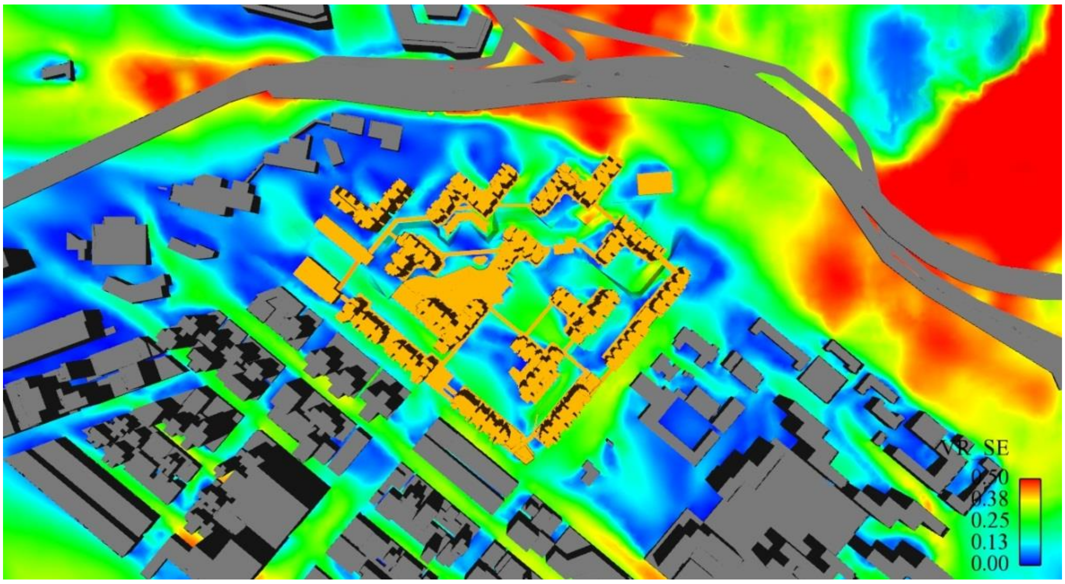

Figure 64 Contour Plot under SE Direction (Proposed Scheme)

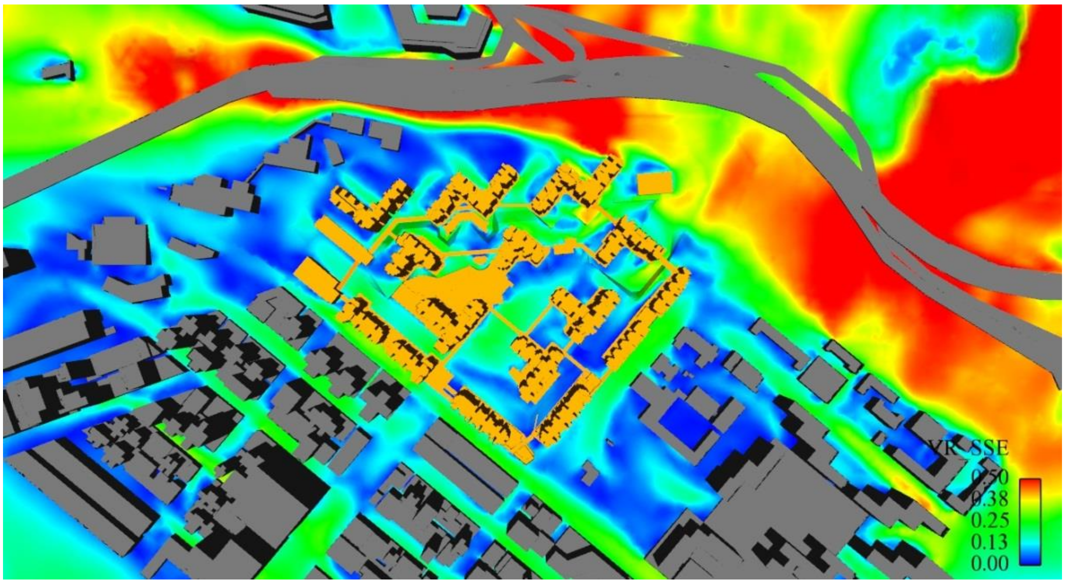

Figure 65 Contour Plot under SSE Direction (Proposed Scheme)

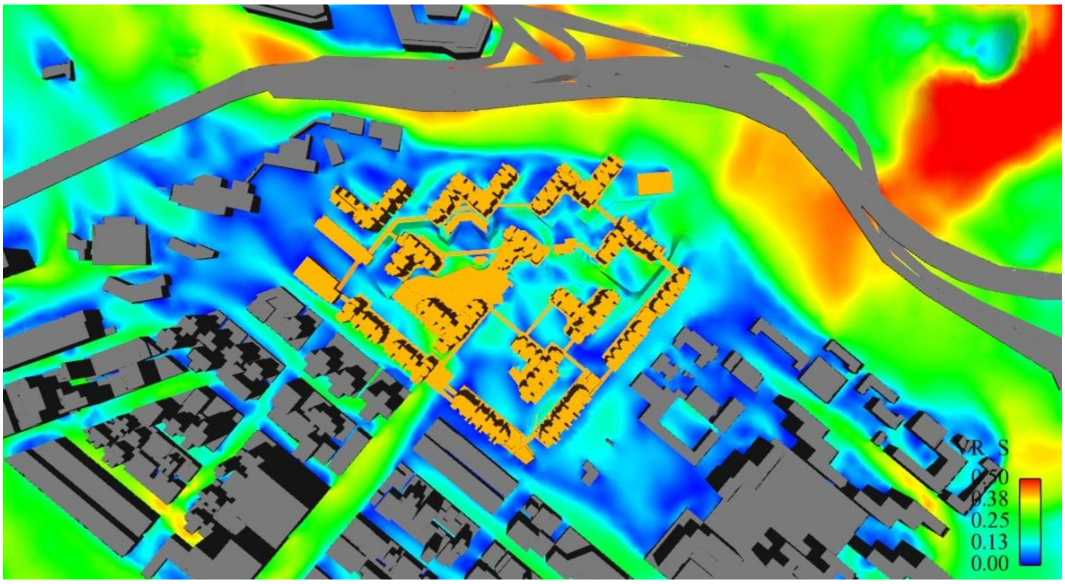

Figure 66 Contour Plot under S Direction (Proposed Scheme)

Appendix C

Directional VR Vector Plot

C1 Directional Vector Plot in Baseline Scheme

Figure 67 Vector Plot under NNE Direction (Baseline Scheme)

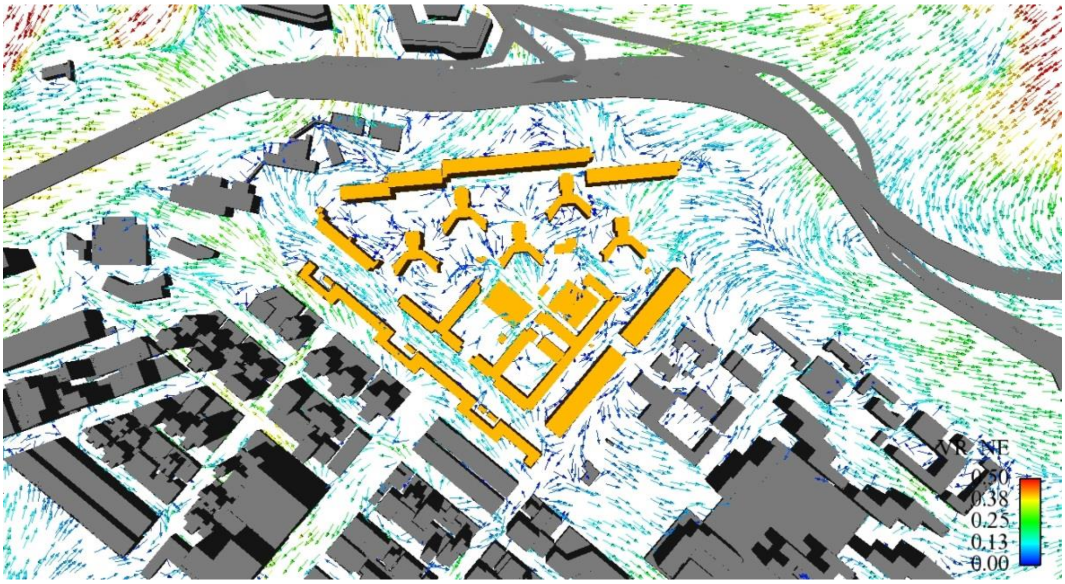

Figure 68 Vector Plot under NE Direction (Baseline Scheme)

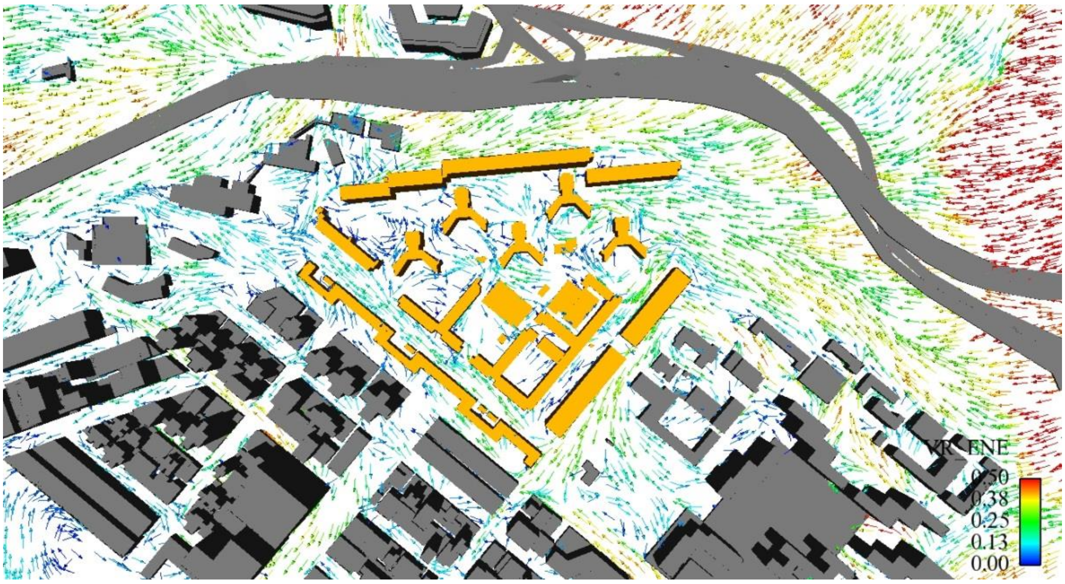

Figure 69 Vector Plot under ENE Direction (Baseline Scheme)

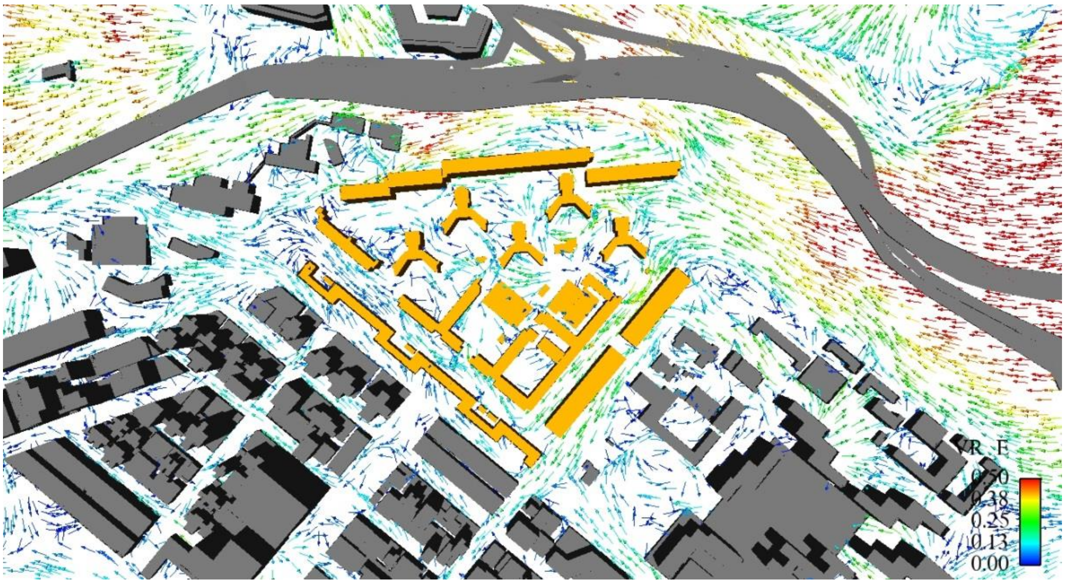

Figure 70 Vector Plot under E Direction (Baseline Scheme)

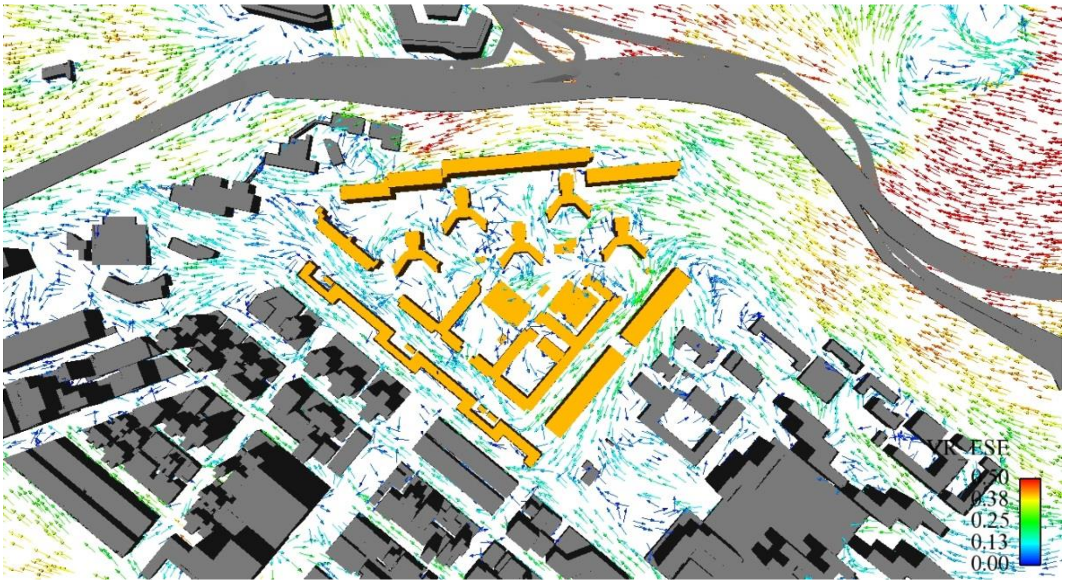

Figure 71 Vector Plot under ESE Direction (Baseline Scheme)

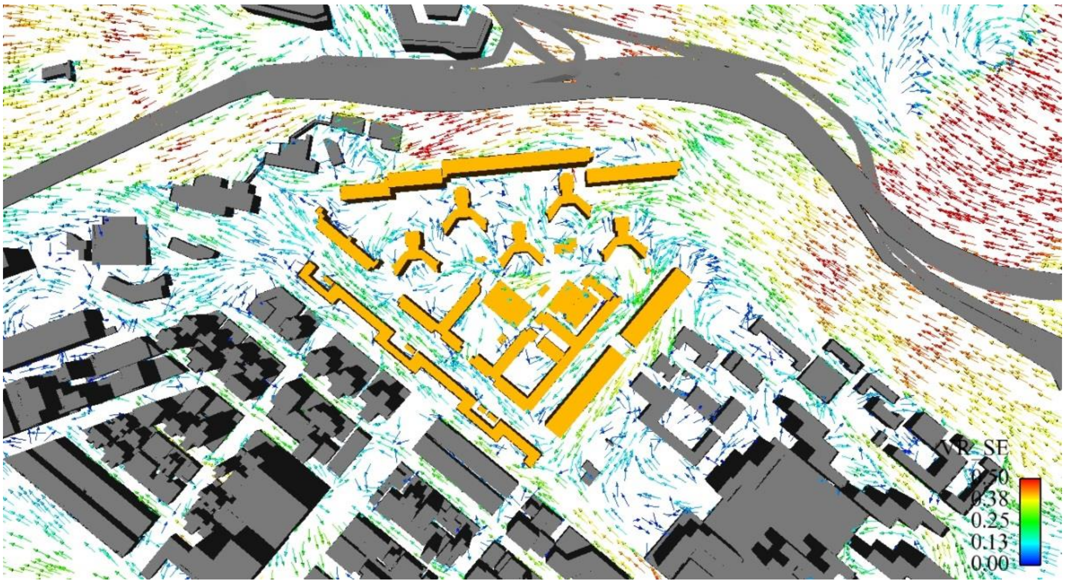

Figure 72 Vector Plot under SE Direction (Baseline Scheme)

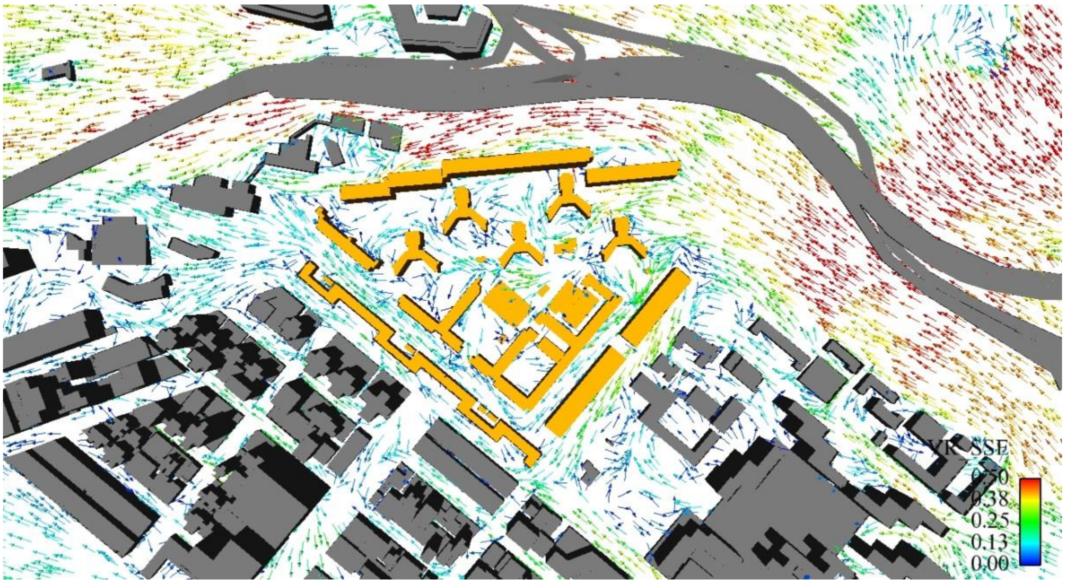

Figure 73 Vector Plot under SSE Direction (Baseline Scheme)

Figure 74 Vector Plot under S Direction (Baseline Scheme)

C2 Directional Vector Plot in Proposed Scheme

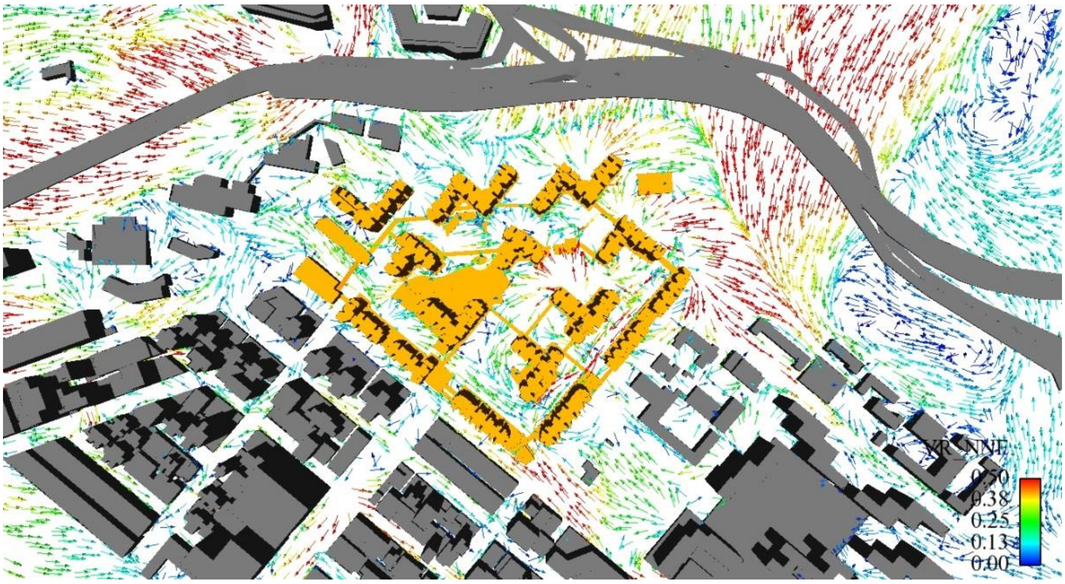

Figure 75 Vector Plot under NNE Direction (Proposed Scheme)

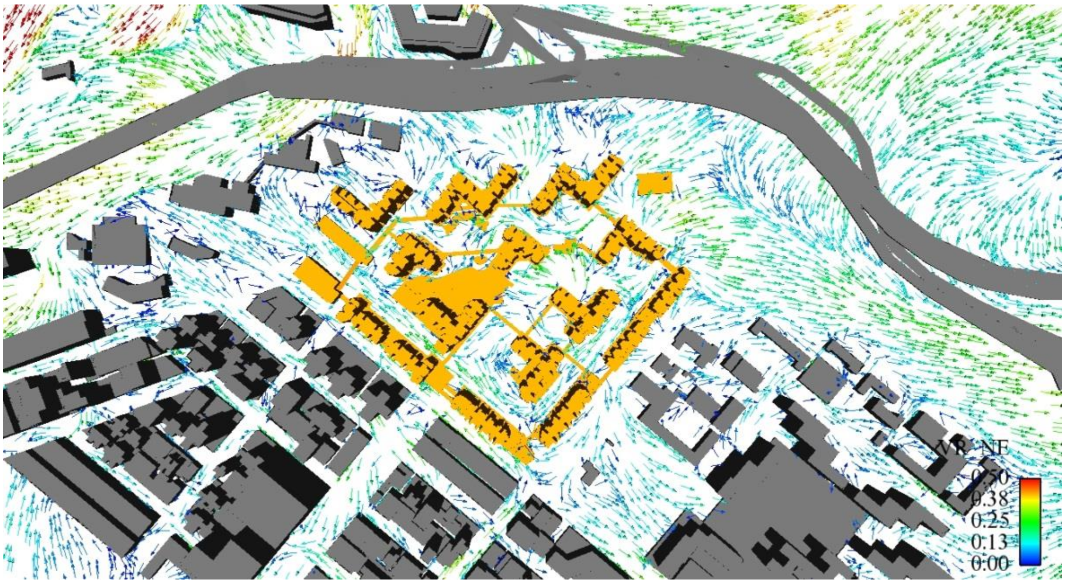

Figure 76 Vector Plot under NE Direction (Proposed Scheme)

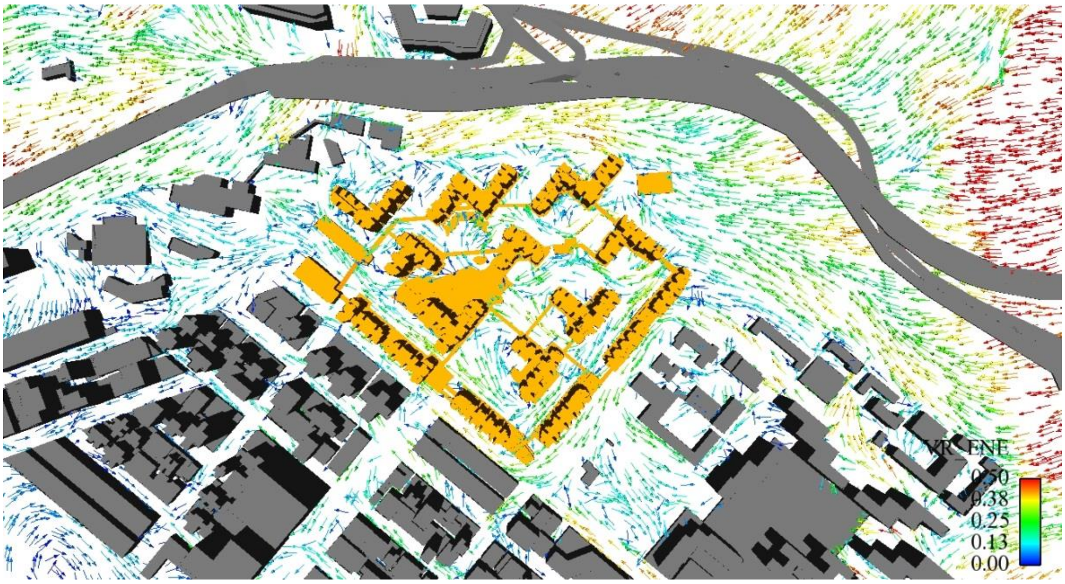

Figure 77 Vector Plot under ENE Direction (Proposed Scheme)

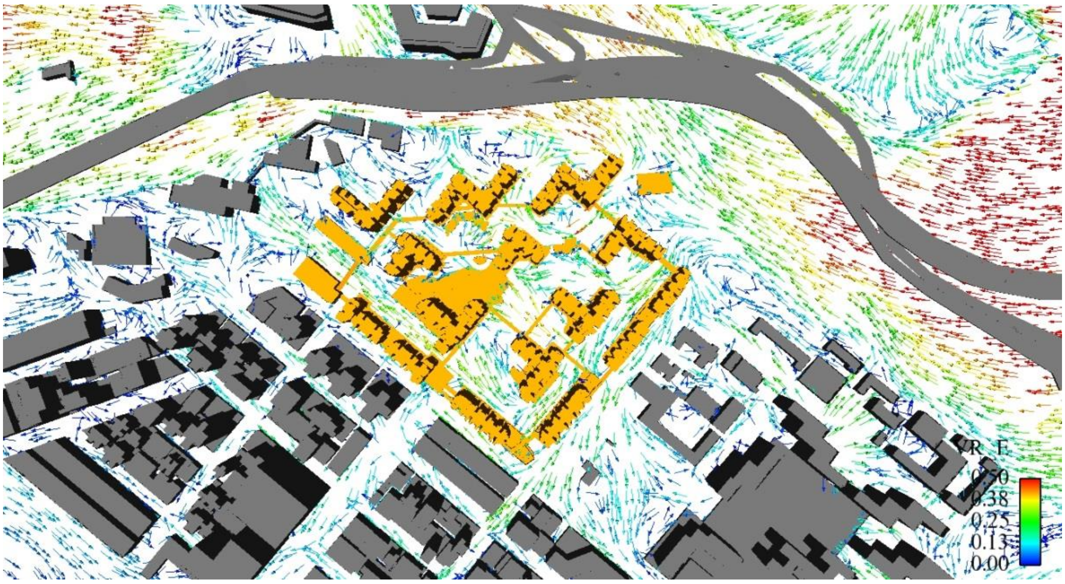

Figure 78 Vector Plot under E Direction (Proposed Scheme)

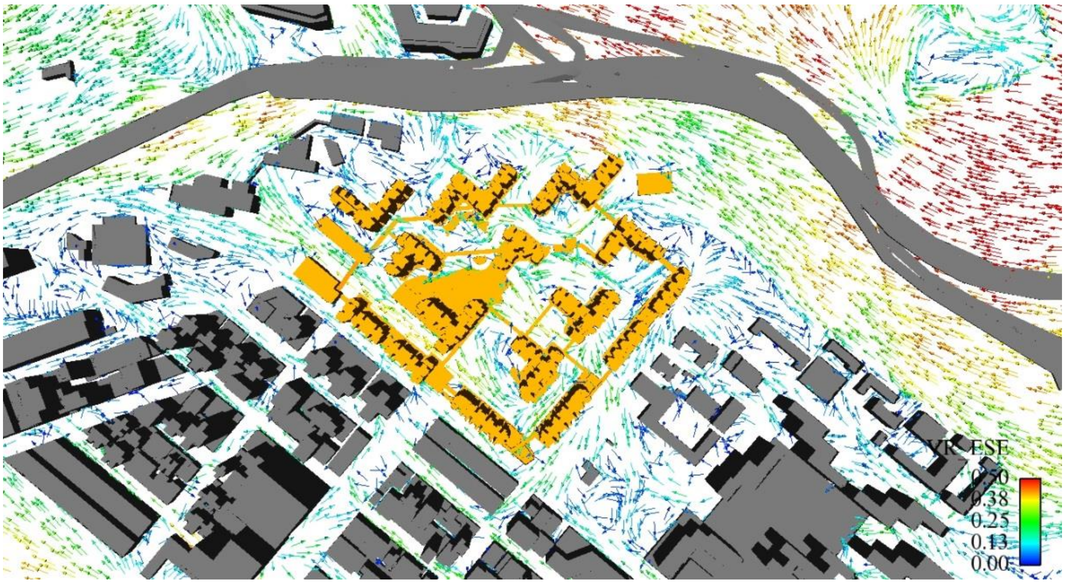

Figure 79 Vector Plot under ESE Direction (Proposed Scheme)

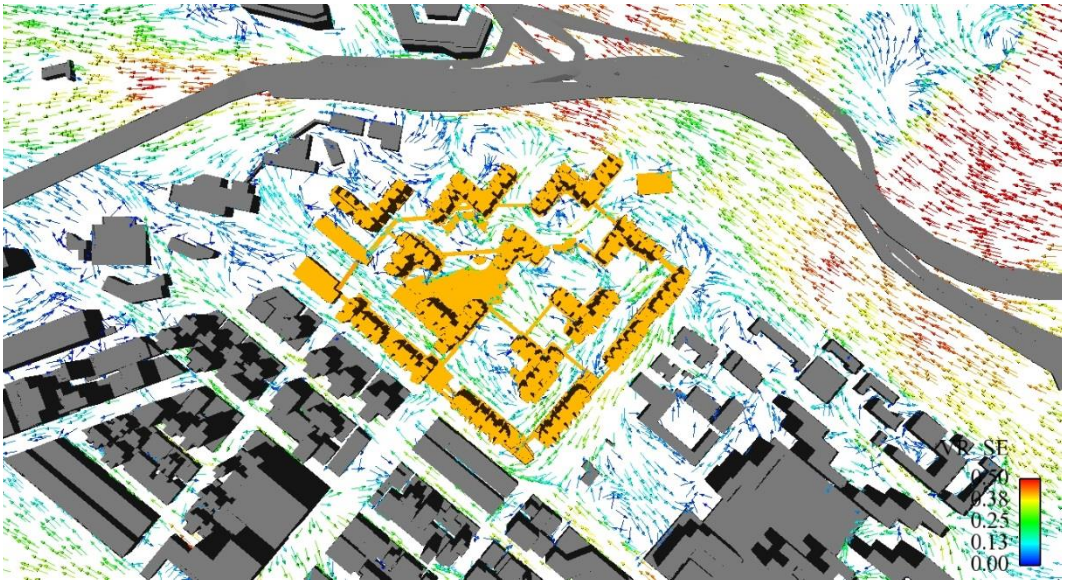

Figure 80 Vector Plot under SE Direction (Proposed Scheme)

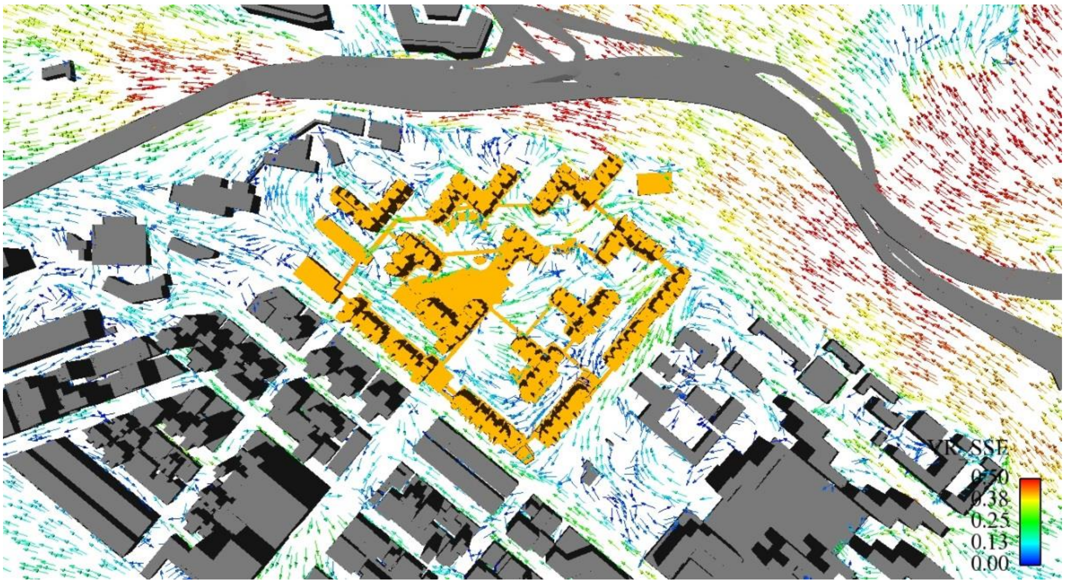

Figure 81 Vector Plot under SSE Direction (Proposed Scheme)

Figure 82 Vector Plot under S Direction (Proposed Scheme)