Hong Kong Housing Authority

Proposed Public Housing Development at Fanling Area 36 Phase 4

Air Ventilation Assessment – Initial Study

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Job number --

Ove Arup & Partners Hong Kong Ltd
Level 5 Festival Walk
80 Tat Chee Avenue
Kowloon Tong
Kowloon
Hong Kong
www.arup.com

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1 Introduction

1.1 Project Background

Ove Arup and Partners Hong Kong Ltd (Arup) was appointed by Hong Kong Housing Authority (HKHA) as the consultant to carry out an Air Ventilation Assessment (AVA) Initial Study for Proposed Public Housing Development at Fanling Area 36 Phase 4 (the Development).

The AVA Initial Study will be conducted to investigate air ventilation performance of the Development, using Computational Fluid Dynamics (CFD) technique.

1.2 Study Objectives

The objectives of the study are:

- To identify the site wind characteristics at the Development and the surrounding area;
- To evaluate the general ventilation pattern over the assessment area;
- To assess the ventilation performance at the focus areas;
- To identify problem areas and propose mitigation measures as appropriate; and
- To demonstrate good design features of the Development.

2 Site Characteristics

2.1 Site Location and the Surrounding Area

The Development is located at the junction of Ching Hiu Road and Pak Wo Road. To the east and southeast of the Development, there are mainly low-rise buildings of Eden Garden and Kai Leng Tsuen; to the southwest there are high-rise residential buildings of Ching Ho Estate; to the west there are high-rise residential buildings of Royal Green, Glorious Peak, and 8 Royal Green; and to the north there is a mid-rise Sheung Shui Government Secondary School. The site location and the surrounding developments are presented in Figure 1.

Site Boundary
Existing Development

Figure 1 Site and the Surrounding Area of the Development

3 Site Wind Availability

This Initial Study follows the methodology for AVA as stipulated in "Technical Circular No. 1/06 – Air Ventilation Assessments" (the Technical Circular) and Annex A to the Technical Circular "Technical Guide for Air Ventilation Assessment for Developments in Hong Kong" (the Technical Guide) jointly issued by Housing, Planning and Lands Bureau and Environmental, Transport and Works Bureau on 19th July 2006 [1].

3.1 Site Wind Availability Data

The site wind availability data for the study is obtained from Planning Department's website, which was simulated using the meso-scale numerical model Regional Atmospheric Modelling System (RAMS) [1]. The location of the Development falls within the location grid (x:071, y:081) in the RAMS database as indicated in Figure 2. The wind rose at 500mPD for annual condition is presented in Figure 3, and is adopted for this study.

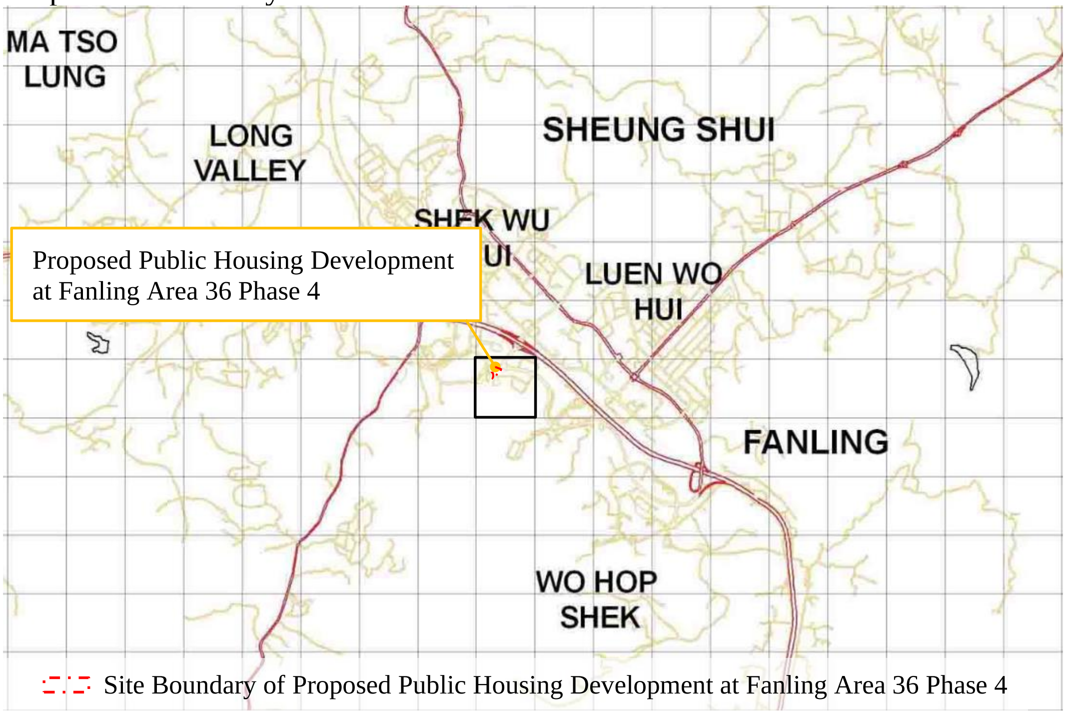


Figure 2 RAMS Grid and Location of the Developments

[1] https://www.devb.gov.hk/filemanager/en/content_679/hplb-etwb-tc-01-06.pdf

Wind rose at 500m height is selected to investigate prevailing wind condition in the Initial Study, as the wind is unaffected by the urban roughness value.

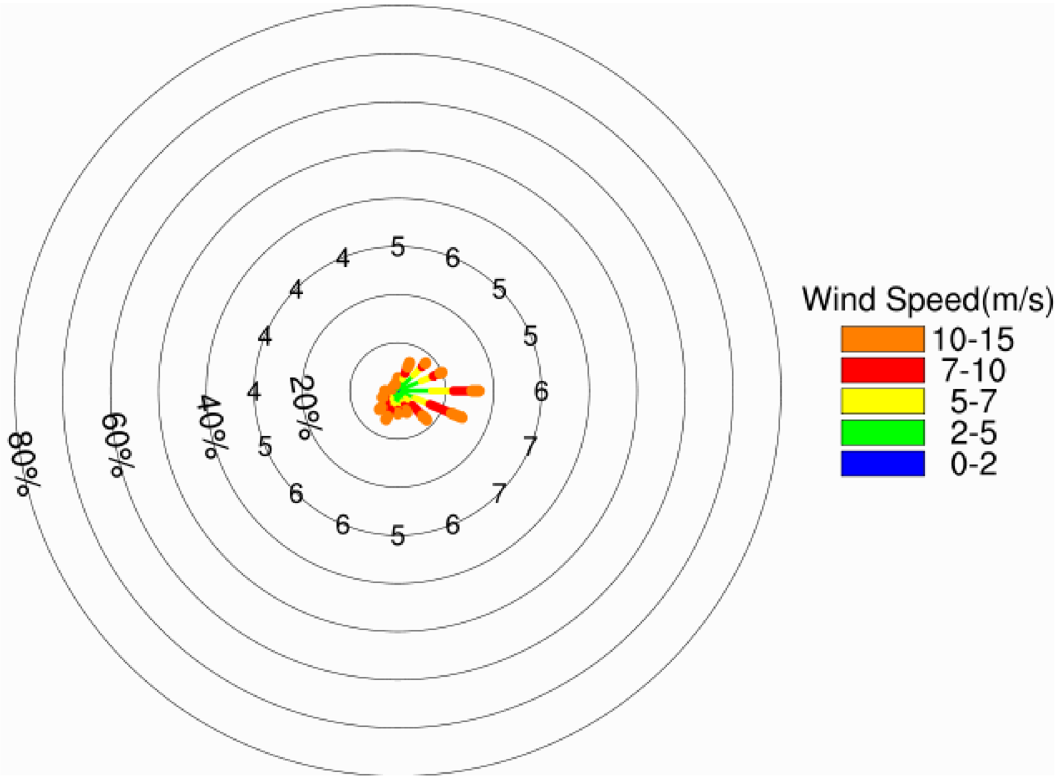


Figure 3 Wind Rose at 500mPD for Annual Condition (Grid x:071, y:081)

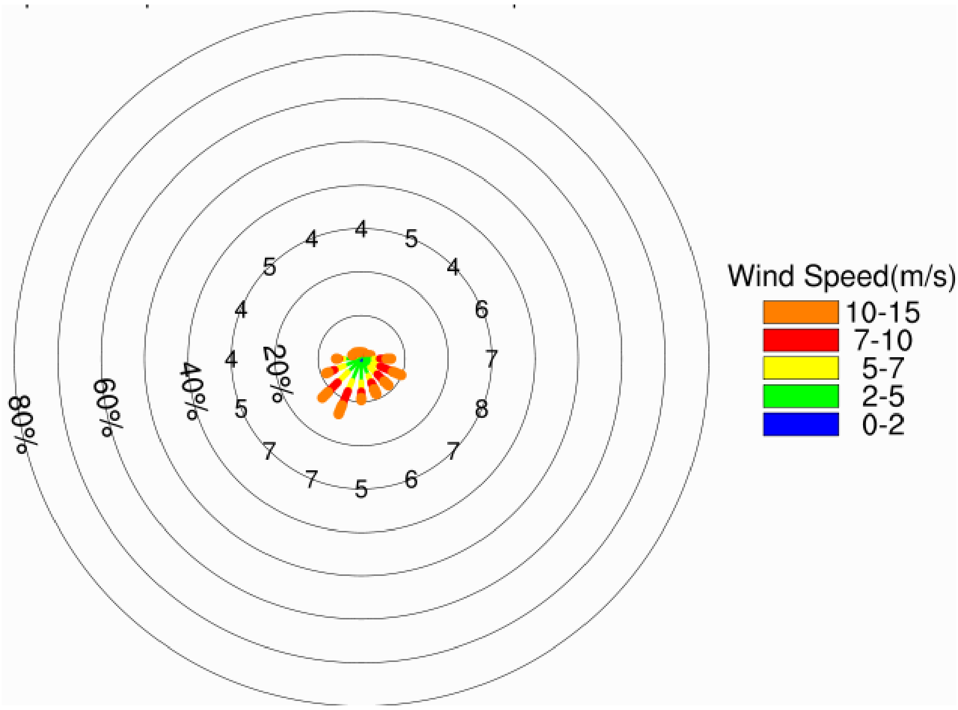


Figure 4 Wind Rose at 500mPD for Summer Condition (Grid x:071, y:081)

4 Methodology for Initial Study

4.1 Wind Directions

As mentioned in Section 3.1, the RAMS wind data of location grid (x:071, y:081) is adopted for the site wind availability in this study.

4.1.1 Annual Prevailing Wind

For annual condition, eight prevailing wind directions (highlighted in red colour in Table 1) are considered in the Initial Study, which cover 77.3% of the total annual wind frequency. They are north-north-easterly (6.4%), north-easterly (8.2%), east-north-easterly (10.2%), easterly (17.2%), east-south-easterly (14.7%), south-easterly (8.6%), south-south-westerly (6.5%) and south-westerly (5.5%) winds.

Table 1 Annual Wind Frequency of the Wind Directions

Wind Direction	N	NNE	NE	ENE	E	ESE	SE	SSE	
Frequency	2.7%	6.4%	8.2%	10.2%	17.2%	14.7%	8.6%	4.9%	
Wind Direction	S	SSW	SW	WSW	W	WNW	NW	NNW	**SUM**
Frequency	4.8%	6.5%	5.5%	3.5%	2.7%	1.3%	1.2%	1.5%	**77.3%**

** The wind directions in red are selected for the study for annual condition*

4.1.2 Summer Prevailing Wind

For summer condition, eight prevailing wind directions (highlighted in red colour in Table 2) are considered in the Initial Study, which cover 81.0% of the total summer wind frequency. They are easterly (7.3%), east-south-easterly (10.3%), south-easterly (8.9%), south-south-easterly (8.9%), southerly (9.7%), south-south-westerly (14.0%), south-westerly (13.0%) and west-south-westerly (8.9%) winds.

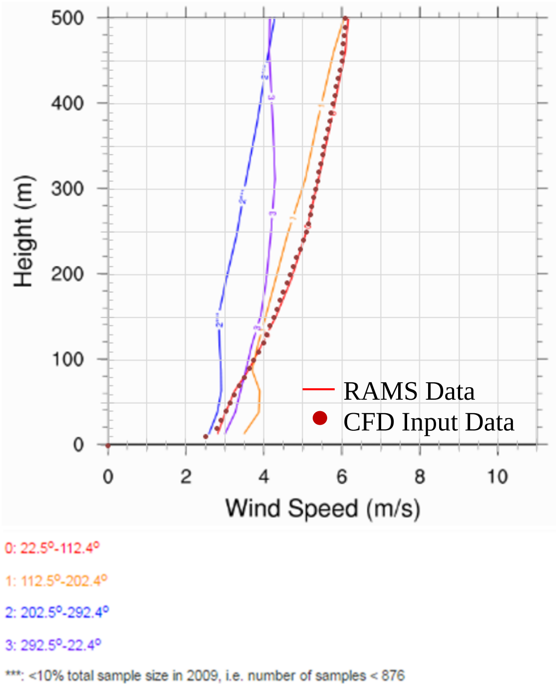
Table 2 Summer Wind Frequency of the Wind Directions

Wind Direction	N	NNE	NE	ENE	E	ESE	SE	SSE	
Frequency	1.5%	1.6%	1.4%	2.4%	7.3%	10.3%	8.9%	8.9%	
Wind Direction	S	SSW	SW	WSW	W	WNW	NW	NNW	**SUM**
Frequency	9.7%	14.0%	13.0%	8.9%	5.9%	2.3%	2.0%	1.7%	**81.0%**

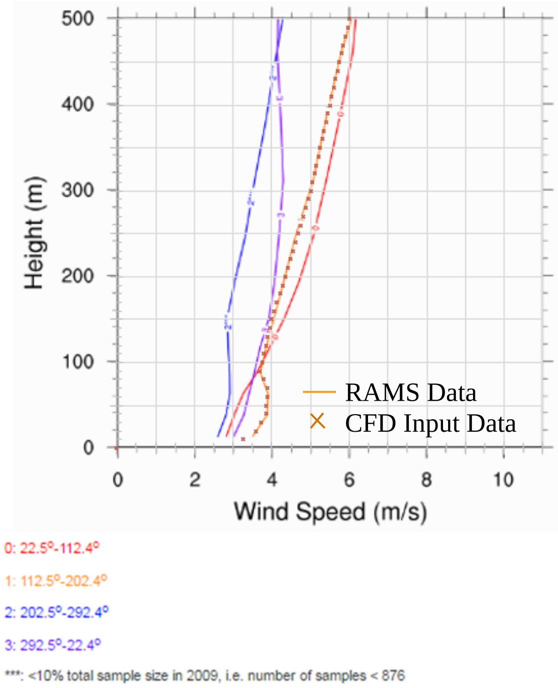
** The wind directions in red are selected for the study for summer condition*

4.2 Wind Profiles

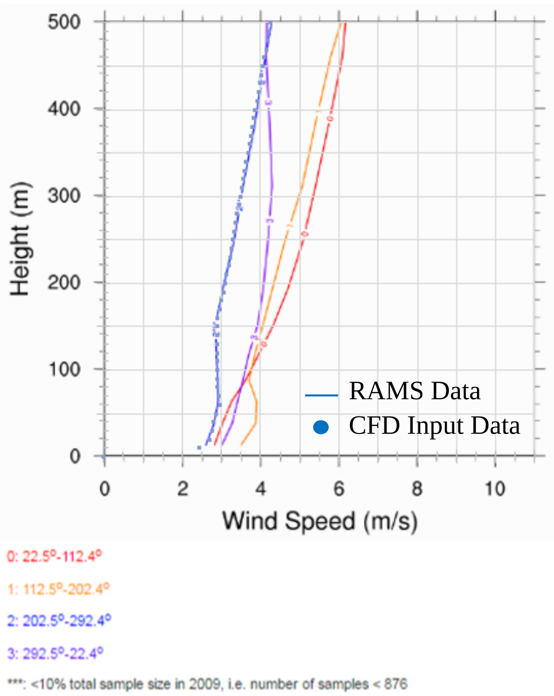
The wind profile calculated from RAMS is adopted in this AVA study. The profiles of wind speed from the PlanD RAMS database (x:071, y:081) are shown in Figure 5. RAMS wind profile data from 10 – 500m is extracted directly as it reflects the exact wind data. For the near ground wind speed from 0 to 10m, the power law equation is used to approximate near ground wind profile. For wind data above 500m height, the velocity is assumed the same as the data at 500m. These wind data will be the input parameters in the CFD simulation. And the wind profiles of the 16 wind directions, categorised into 4 sectors, the simulated wind profile under 4 sectors are presented in Figure 5.



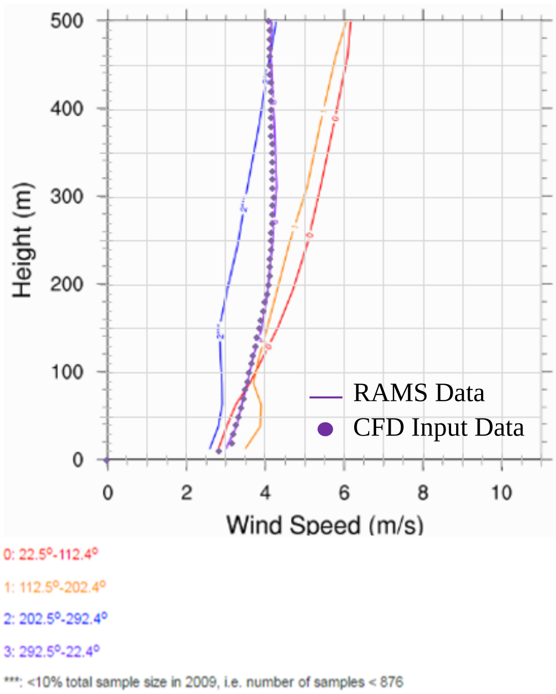
Simulated wind profile from 22.5° – 112.4°



Simulated wind profile from 112.5° – 202.4°



Simulated wind profile from 202.5° – 292.4°



Simulated wind profile from 292.5° – 22.4°

Figure 5 Wind Profile from RAMS at the Project Site (Grid x:071, y:081)

4.3 Technical Details of CFD Simulations

The Air Ventilation Assessment (AVA) methodology as stipulated in the Technical Circular and Technical Guide is used for this study. The following sections describe the details of the study methodology.

4.3.1 Project Assessment and Surrounding Areas

With reference to the Technical Guide, the Assessment Area would include the immediate surroundings of the development, up to 1H from the site boundary where H is the height of the tallest building of the development. The Surrounding Area would include the area up to 2H from the site boundary.

The tallest building of the Development has a building height of about 125m, so 1H and 2H would be 125m and 250m respectively. The site boundary, Assessment Area, and Surrounding Area of the study are presented in Figure 6.

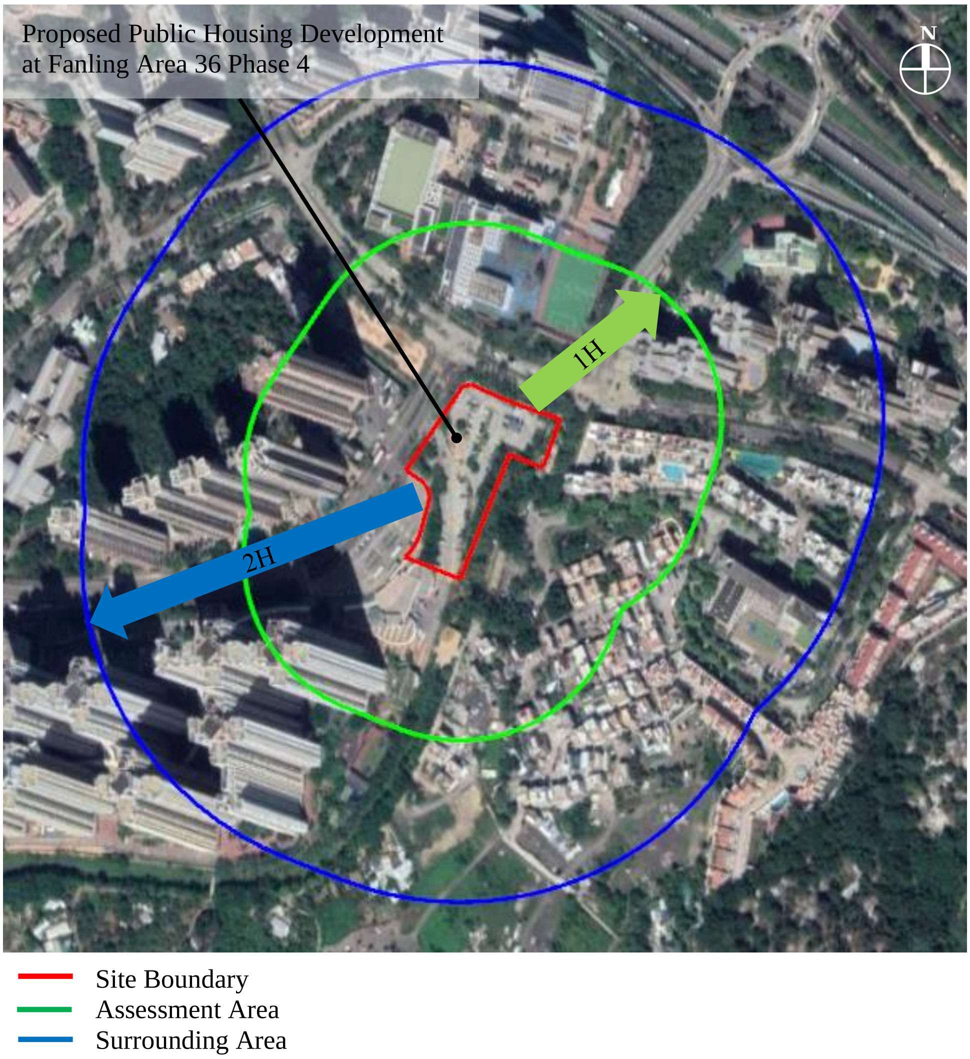


Figure 6 Site boundary, Assessment Area, and Surrounding Area (Image Source: Google Maps)

4.4 CFD Model

Following the Technical Circular for AVA, buildings within Surrounding Area shall be built in the CFD model. In addition, the model domain is built far beyond the Surrounding Area as required in the Technical Circular in order to eliminate the boundary effects. Therefore, the studied size of the CFD model for this Study is approximately 2400m (L) x 2400m (W) x 2000m (H). It covers the Development and provides sufficient consideration on surrounding topography. The model contains information of the surrounding buildings and topography from Geographical Information System (GIS) platform.

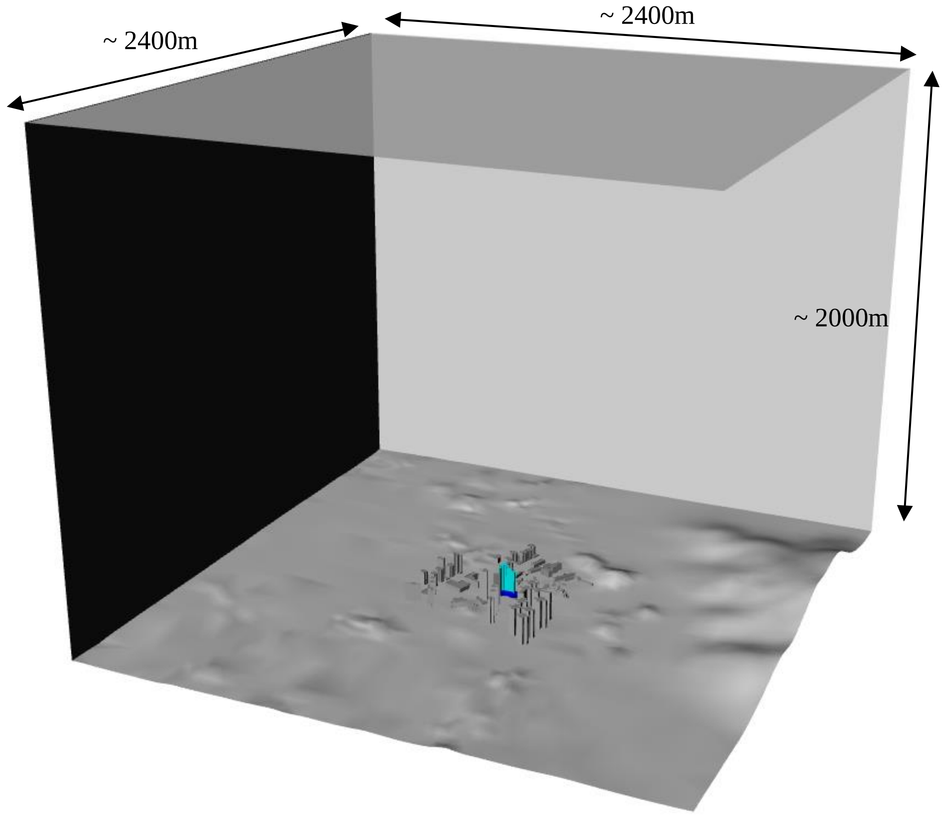


Figure 7 Domain of CFD model

4.5 Assessment Tool

Computational Fluid Dynamics (CFD) technique was adopted to assess the wind environment of the Development. Well recognised commercial CFD packages ANSYS ICEM-CFD and STAR-CCM+ are used, where both software are widely used in the industry for air ventilation studies. With the use of three-dimensional CFD method, the local airflow distribution can be visualised in detail. The air velocity distribution within the flow domain, being affected by the site-specific design and the surrounding buildings, is simulated under the prevailing wind conditions. The nearby surrounding buildings and the site topography was constructed as shown in Figure 8. The CFD model is constructed according to the layout plan of the development.

— Site Boundary of the Development
The Development
Surrounding Development

Figure 8 Model of the Development and its Surroundings

4.5.1 Mesh Setup

Body-fitted unstructured grid technique is used to fit the geometry to reflect the complexity of the development geometry. A prism layer of 3m above ground (totalling 6 layers and each layer is 0.5m) is incorporated in the meshing so as to better capture the approaching wind. The expansion ratio is 1.3 while the maximum blockage ratio is 3%.

Finer grid system is applied to the most concerned area based on preliminary judgement, while coarse grid system is applied to the area of surrounding buildings for better computational performance while maintaining satisfactory result.

4.5.2 Turbulence Model

As highlighted in recent academic and industrial research literatures by CFD practitioners, the widely used standard k - ε turbulence model technique may not 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 turbulence modelling method is applied. This technique provides more accurate representation of the levels of turbulence that can be expected in an urban environment.

4.5.3 Calculation Method

The Segregated Flow model solves the flow equations in a segregated 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 differencing scheme is applied to discretize the governing equations. The convergence criterion is set to 1.0×10^{-4} on mass conservation. The calculation will repeat until the solution satisfies this convergence criterion.

The prevailing wind direction as mentioned in Section 4.1 is set to inlet boundary of the model with wind profile as detailed in Section 4.2. The downwind boundary is set to pressure with value of atmospheric pressure. The top and side boundaries are set to symmetry.

4.5.4 Summary

Based on previous sections, the key parameters of the CFD model are summarized in Table 3.

Table 3 Key Parameters of the CFD model

Parameter	Modelling Detail
Physical Model Scale	Real Scale model, 1:1 scale
Model details	Only include Topography, Building Blocks, Streets/Highways, no Landscape is included
Domain	2400m(L) x 2400m(W) x 2000m(H)
Assessment Area	1H from Site Boundary
Surrounding Area	2H from Site Boundary
Grid Expansion Ratio	The grid should satisfy the grid resolution requirement with maximum expansion ratio = 1.3
Prismatic layer	6 layer of prismatic layers and 0.5m each (i.e. total 3m above ground)
Inflow boundary Condition	Incoming wind profile as described in Section 3.1
Outflow boundary	Pressure boundary condition with dynamic pressure equal to zero
Wall boundary condition	Logarithmic law boundary
Solving algorithms	Rhie and Chow SIMPLE for momentum equation Hybrid model for all other equations
Blockage ratio	< 3%
Convergence criteria	Below 1.0×10^{-4}

4.6 AVA Indicator

The Wind Velocity Ratio (VR) as proposed by the Technical Circular is employed to assess the ventilation performances of the proposed development and surrounding environment. Higher VR implies better ventilation. The calculation of VR is given by the following formula:

$$VR = \frac{V_p}{V_\infty}$$

V_∞= the wind velocity at the top of the wind boundary layer (typically assumed to be around 500m above the centre of the site of concern, or at a height where wind is unaffected by the urban roughness below).

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

The higher the value of VR, the less is the impact due to buildings on wind availability.

The Average VR is defined as the weighted average VR with respect to 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.

4.6.1 Assessment Parameter

CFD simulations were conducted to study the wind environment. As specified in the Technical Circular, indicator of ventilation performance should be the 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) will be determined. The description of the assessment parameters are presented in Table 4.

Table 4 Assessment Parameter of the 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 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 represent the average VR of all points, i.e. perimeter and overall test points at the site boundary which identified in the report.

5 Studied Scenarios

In this study, the potential individual ventilation impact of the proposed changes of the Development is investigated. Thus, there are two (2) scenarios – namely Baseline Scheme, and Proposed Scheme.

5.1 Baseline Scheme

The Baseline Scheme consists of a 4-storey composite podium for retail, carparking and ancillary facilities, and a domestic tower above the podium. The building height is about 130mPD. It is one of the option designs at the early design stage.

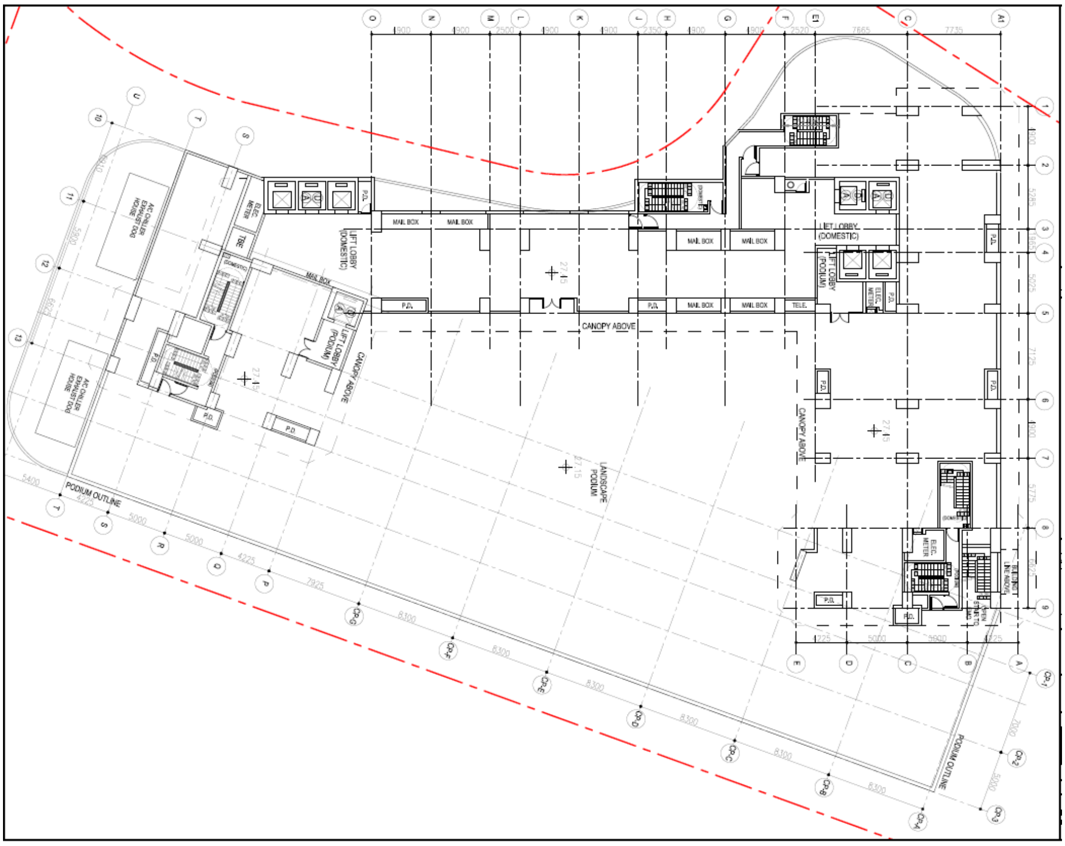


Figure 9 Podium Layout Plan of Baseline Scheme

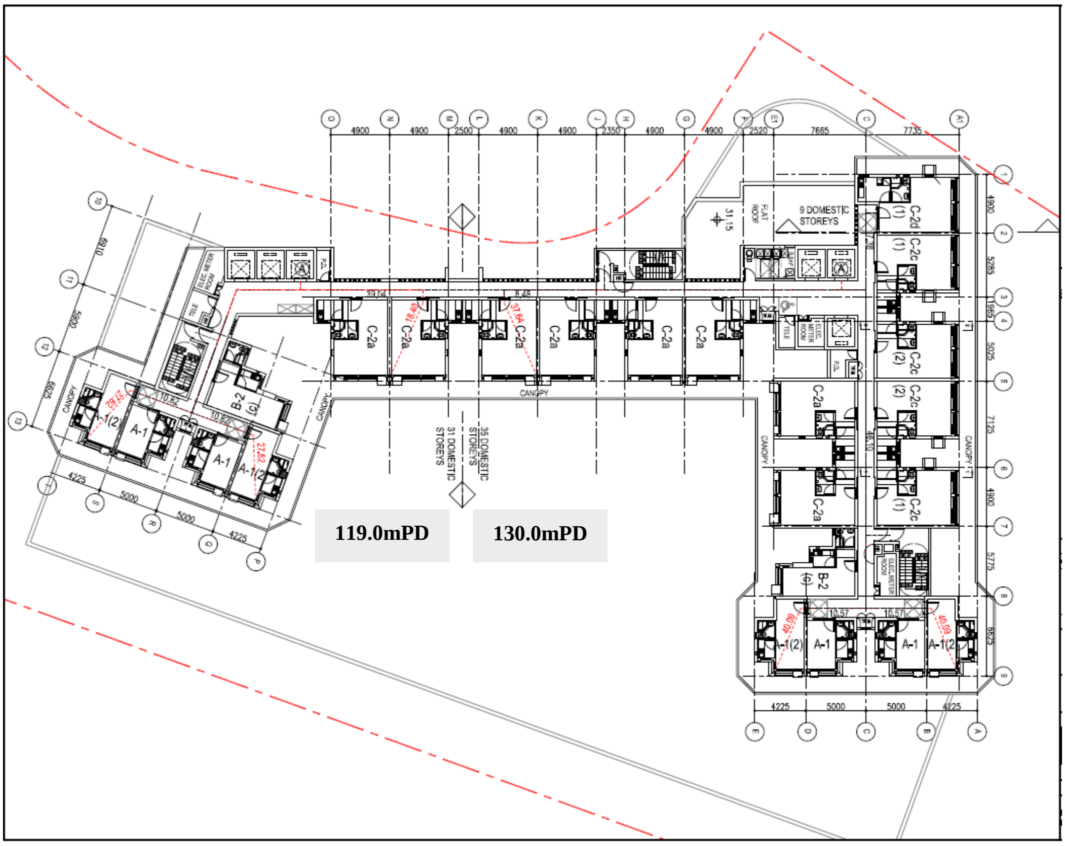


Figure 10 Tower Layout Plan of Baseline Scheme

3D model for Baseline Scheme

Four different views of the 3D models of the Baseline Scheme in this AVA Initial Study are shown below.

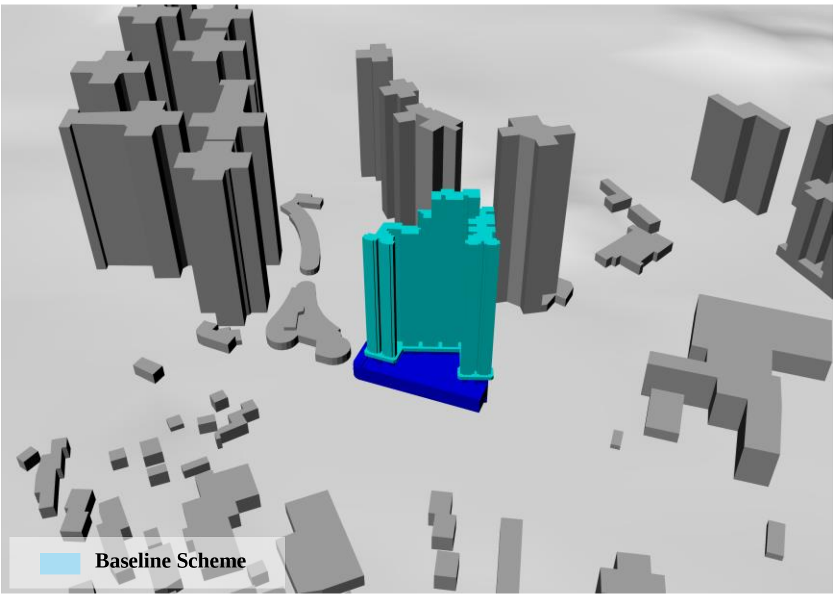


Figure 11 Model of Baseline Scheme, Easterly View

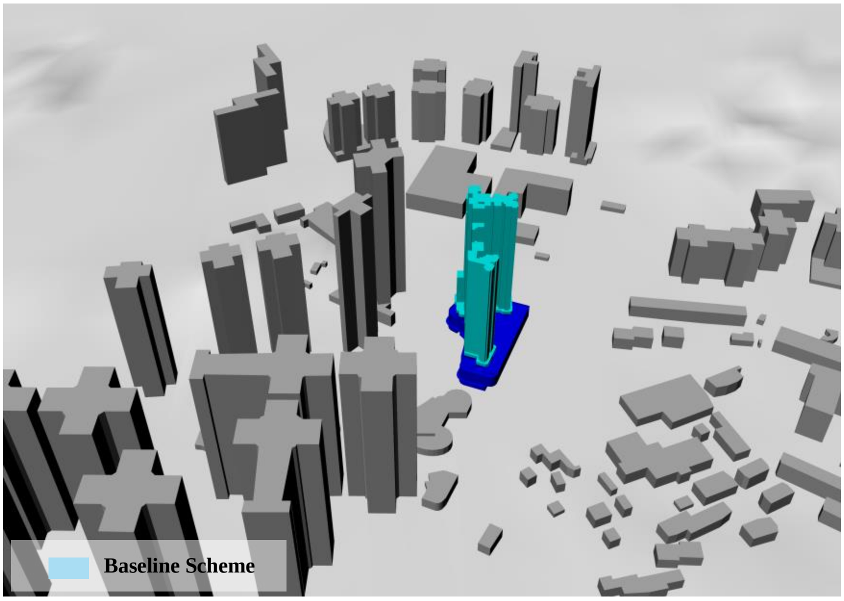


Figure 12 Model of Baseline Scheme, Southerly View

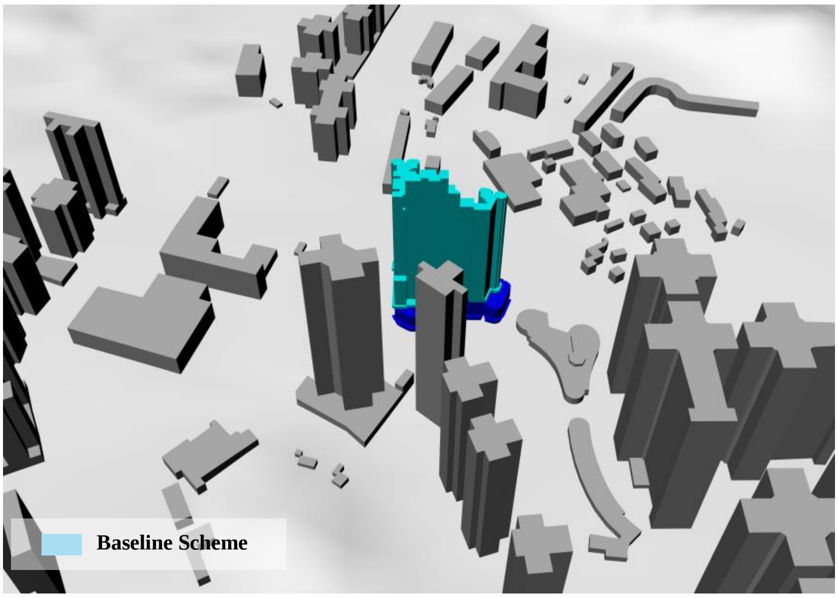


Figure 13 Model of Baseline Scheme, Westerly View Proposed Scheme

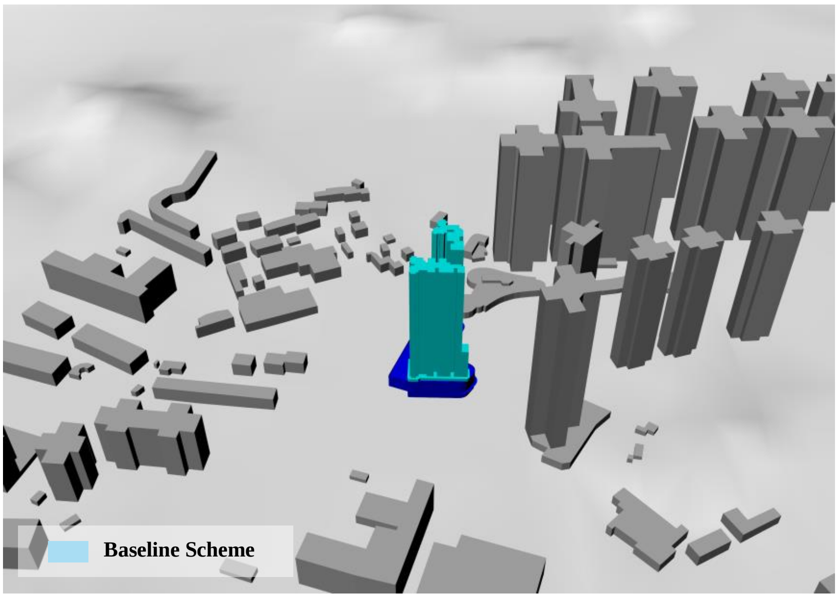


Figure 14 Model of Baseline Scheme, Northerly View

5.2 Proposed Scheme

The Proposed Scheme consists of a 4-storey composite podium for retail, carparking and ancillary facilities, and a domestic tower above the podium. The building height is about 133mPD.

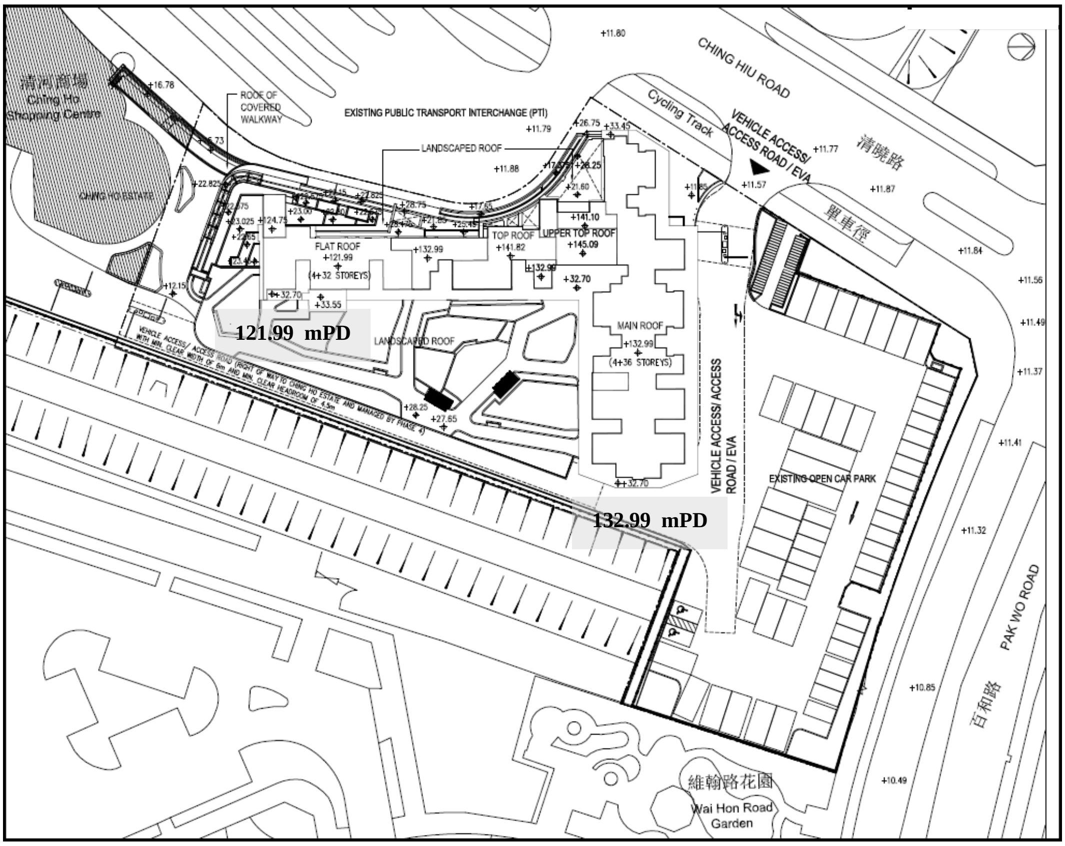


Figure 15 Master Layout Plan of Proposed Scheme

3D model for Proposed Scheme

Four different views of the 3D models of the Proposed Scheme in this AVA Initial Study are shown below.

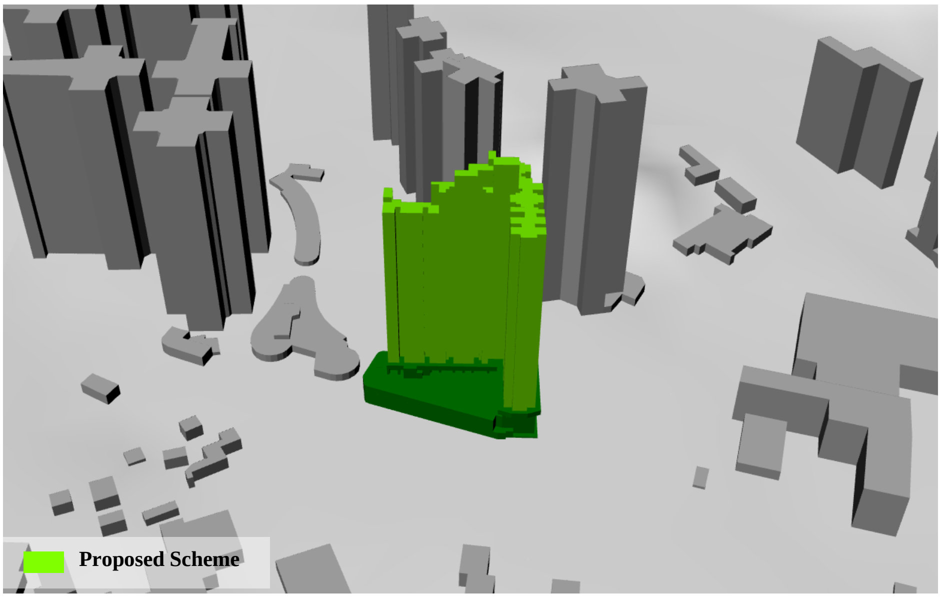


Figure 16 Model of Proposed Scheme, Easterly View

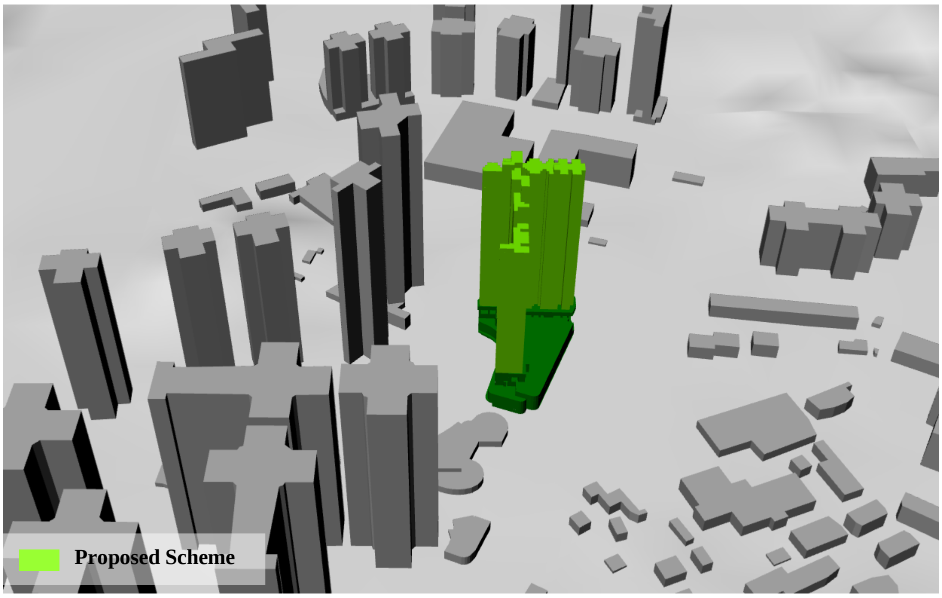


Figure 17 Model of Proposed Scheme, Southerly View

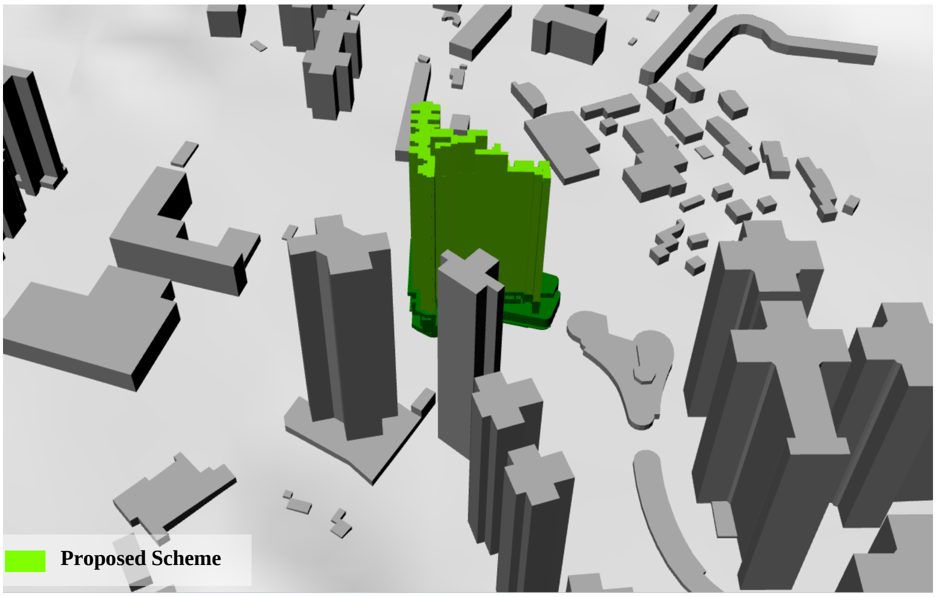


Figure 18 Model of Proposed Scheme, Westerly View

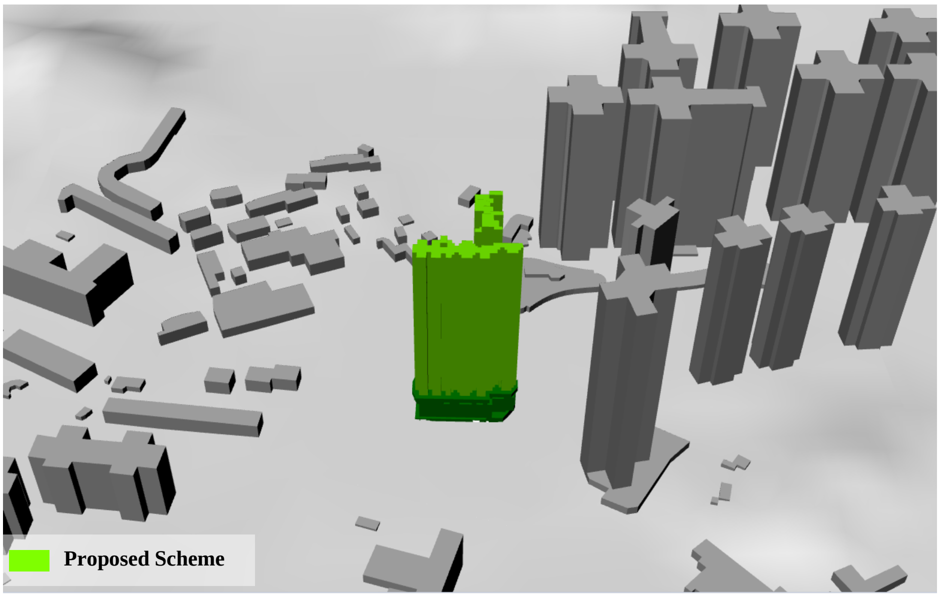


Figure 19 Model of Proposed Scheme, Northerly View

5.3 Test Point Location

Test points are evenly placed along the site boundary and within the assessment area of the Development to determine the ventilation performance. There are two types of test points in the study:

Perimeter Test Points

Perimeter test points are the points positioned at the site boundary of the proposed development. In accordance with the Technical Circular for AVA, perimeter points are positioned at interval of about 15m alongside the site boundary. In total there are 29 perimeter test points (Red Points in Figure 20) in this study.

Overall Test Points

Overall test points are those points evenly positioned in the open area on the streets and places where pedestrian frequently access within the assessment area. In total there are 84 overall test points (**Black Points** in Figure 20) within the assessment area.

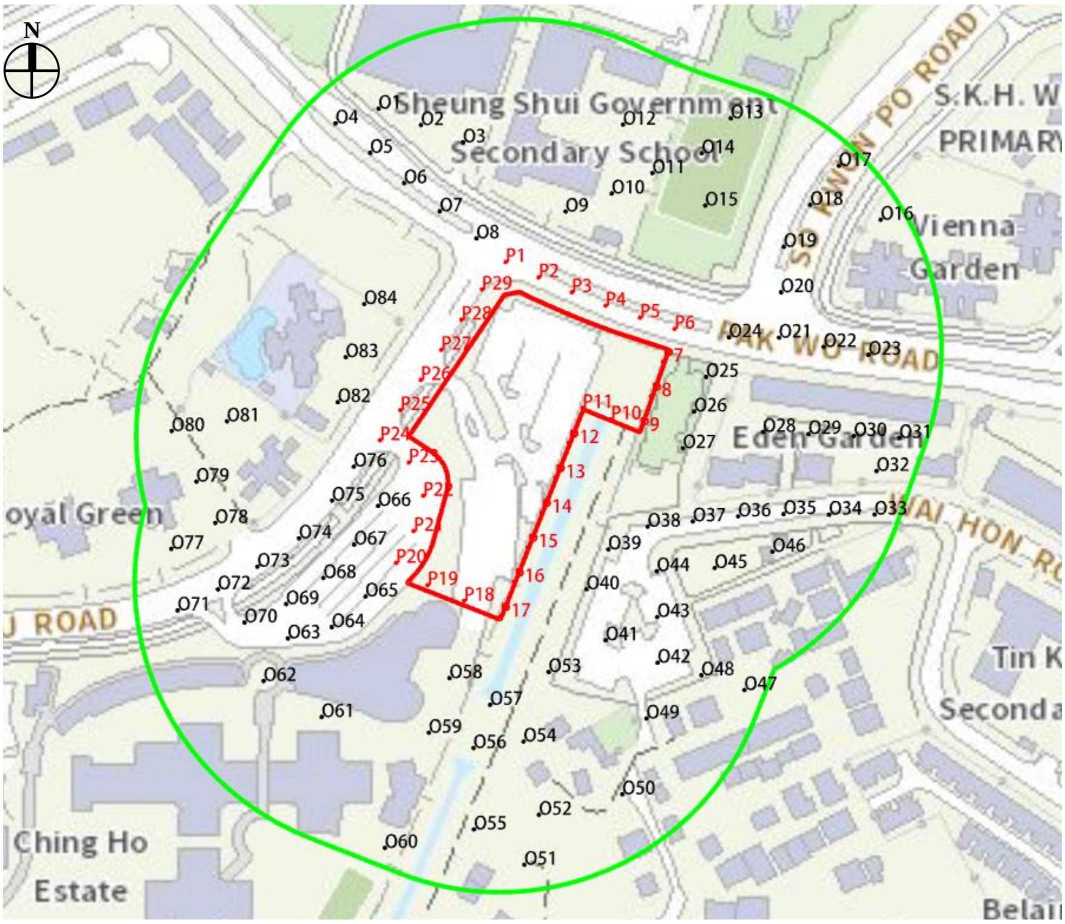


Figure 20 Perimeter and Overall Test Points and Focus Areas

6 Results and Discussion

The Wind Velocity Ratio (VR) as proposed by the Technical Circular was employed to assess the ventilation performances of the Development and surrounding environment. VR is 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. Higher VR implies better ventilation.

The Site spatial average velocity ratio (SVR) represents the average VR of all perimeter test points at the site boundary. The Local spatial average velocity ratio (LVR) represents the average VR of all perimeter and overall test points. The SVR and LVR under annual and summer conditions were calculated respectively.

6.1 Overall Ventilation Performance

6.1.1 Annual Condition

For the annual condition, eight wind directions were studied, accumulating to 77.3% occurrence frequency. The integrated effect of these winds indicates the annual overall ventilation performance. The major prevailing winds under annual wind condition come from north-eastern and south-eastern quarters.

Under annual condition, the values of SVR and LVR are same under Baseline Scheme and Proposed Scheme, indicating that the ventilation performance of the two schemes at the immediate area and local surrounding would be generally similar.

Table 5 SVR and LVR under Annual Condition

	Baseline Scheme	Proposed Scheme
SVR	0.25	0.25
LVR	0.21	0.21

The VR contour plots under Baseline Scheme and Proposed Scheme are shown in Figure 21 and Figure 22 respectively. The VR contour plots show that:

- The overall ventilation performance among the two studied scenarios would be generally similar under annual condition.
- Under Proposed Scheme, the alignment of residential tower and podium at northeast corner would enable more downwash wind to reach pedestrian level and result slightly higher VR at the region to the northeast of the Development (Blue Ellipse in Figure 22).

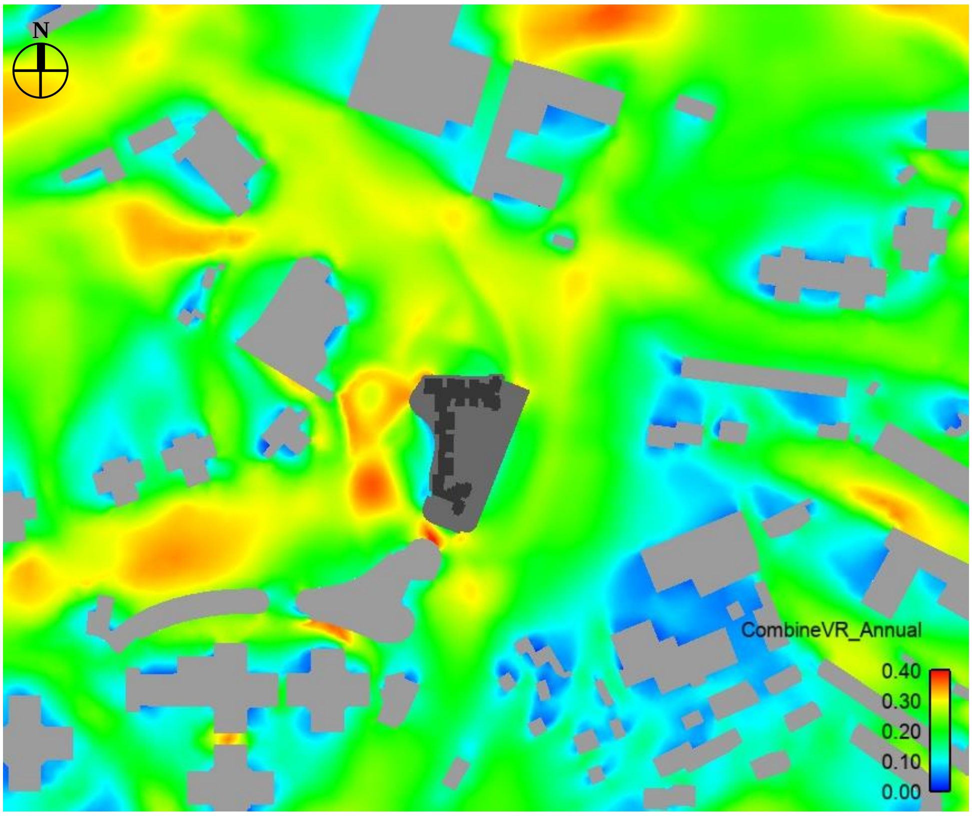


Figure 21 Average Annual VR Contour Plots for Baseline Scheme

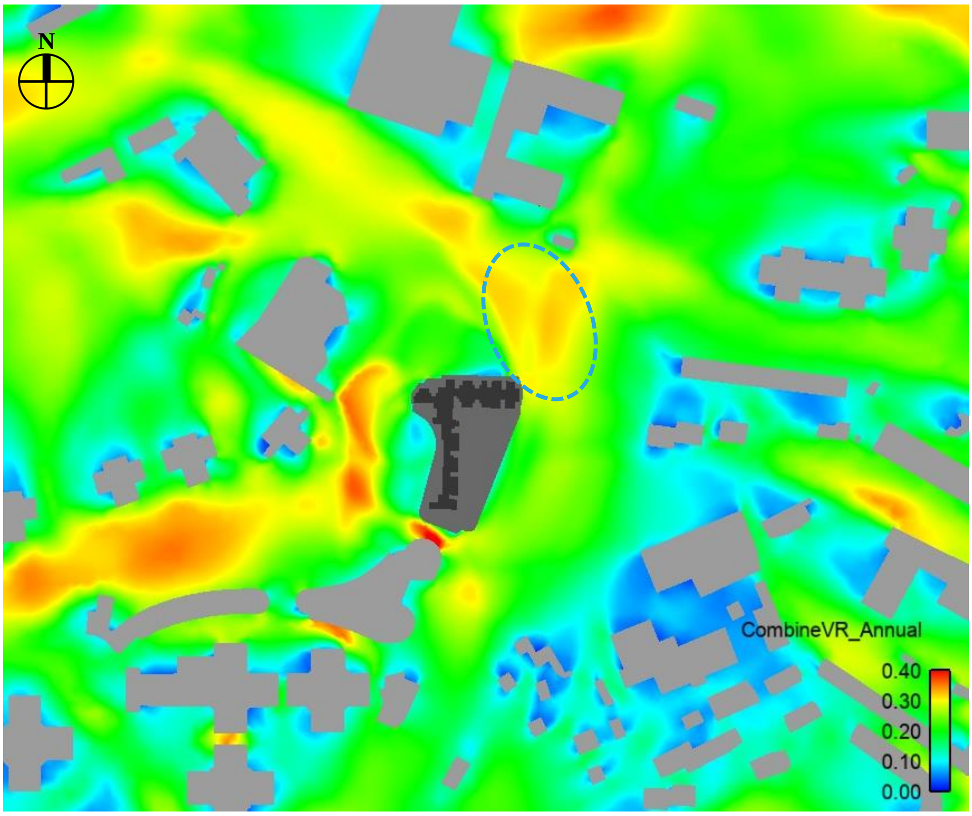


Figure 22 Average Annual VR Contour Plots for Proposed Scheme

6.1.2 Summer Condition

For the summer condition, seven wind directions were studied, accumulating to 81.0% occurrence frequency. The integrated effect of these winds indicates the summer overall ventilation performance. The major prevailing winds under summer wind condition come from south-eastern and south-western quarters.

Under summer condition, the values of SVR and LVR are same under Baseline Scheme and Proposed Scheme, indicating that the ventilation performance of the two schemes at the immediate area and local surrounding would be generally similar.

Table 6 SVR and LVR under Summer Condition

	Baseline Scheme	Proposed Scheme
SVR	0.25	0.25
LVR	0.21	0.21

The VR contour plots under Baseline Scheme and Proposed Scheme are shown in Figure 23 and Figure 24 respectively. The VR contour plots show that:

- The overall ventilation performance for Baseline Scheme and Proposed Scheme would be quite similar under summer condition.
- Under Proposed Scheme, the larger tower frontage facing the south direction, together with the alignment of residential tower and podium edges at the northeast corner, would induce stronger downwash effect towards the pedestrian level. Hence, slightly higher VR could be observed at the region to the north east of the development (Purple Circle in Figure 23).
- Similarly, under Proposed Scheme, the larger building frontage facing the west direction would induce stronger downwash effect towards the pedestrian level. Hence, slightly higher VR could be observed at the region to the west of the development (Orange Ellipse in Figure 23).

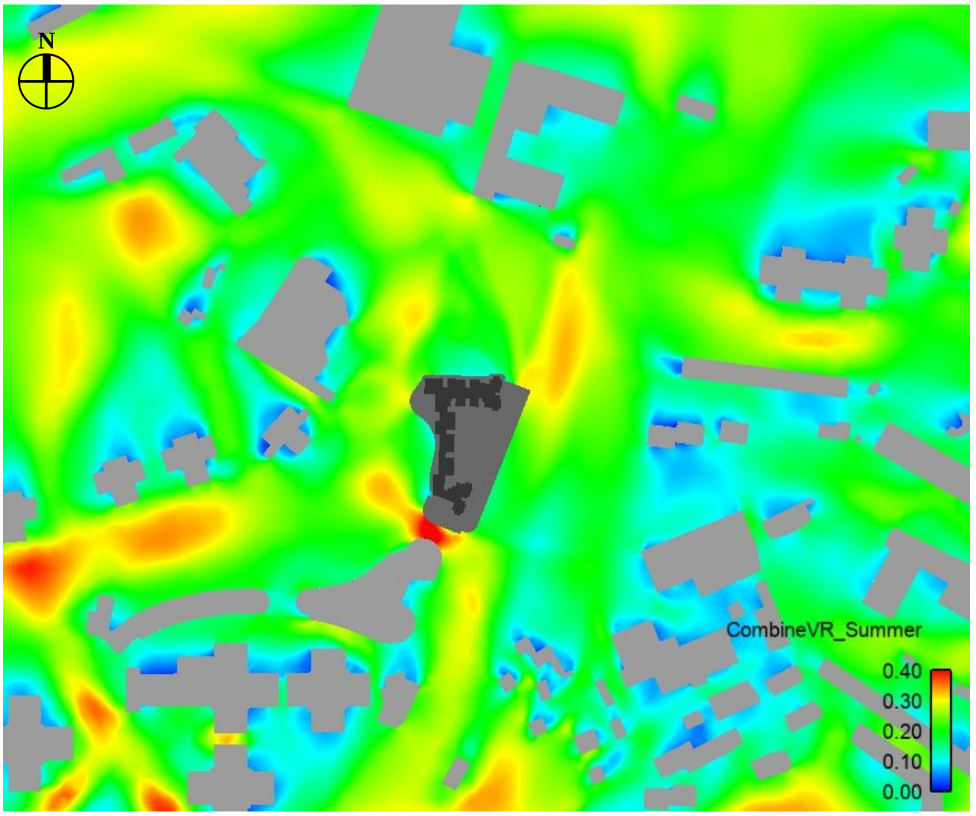


Figure 23 Average Summer VR Contour Plots for Baseline Scheme

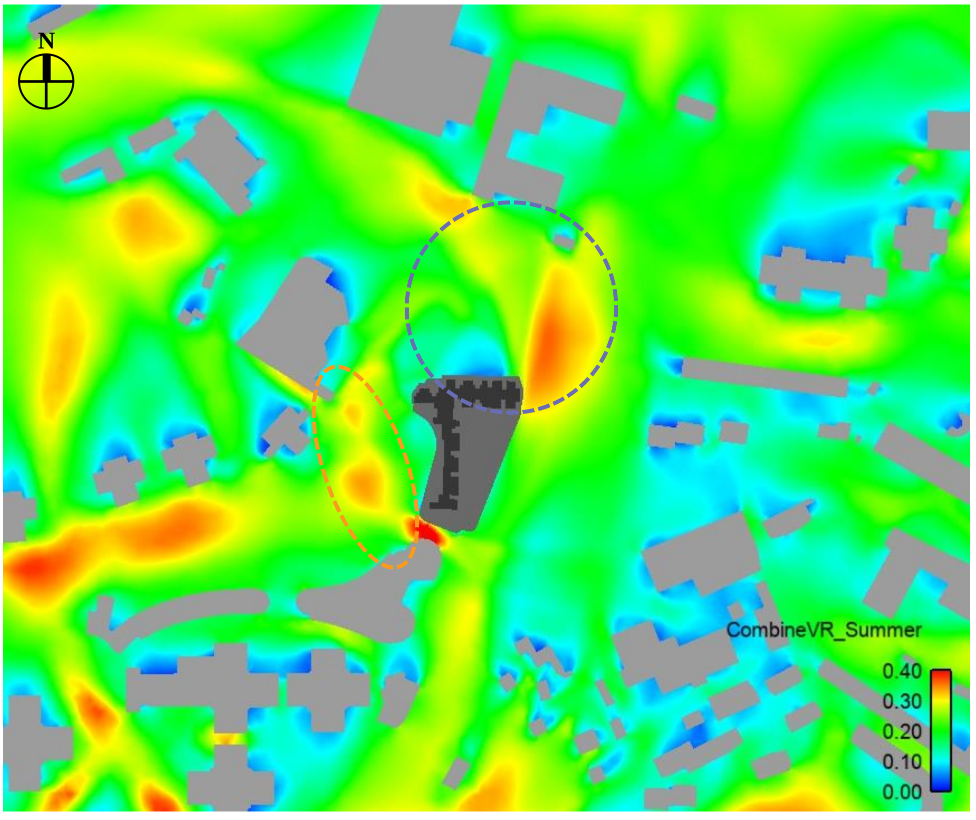


Figure 24 Average Summer VR Contour Plots for Proposed Scheme

6.2 Directional Analysis

6.2.1 NNE Wind

NNE wind contributes approximately 6.4% of the annual wind rose. The VR contour plots under Baseline Scheme and Proposed Scheme are shown in Figure 25 and Figure 26 respectively. In general, the overall ventilation environment is similar among the two schemes.

The incoming wind would reach the north-east corner of the Development with little obstruction, as there are mainly open spaces, e.g. Po Wing Road Playground, and low-rise village houses at the upwind location.

Under Proposed Scheme, west wing of the residential tower extends further towards the south when compared with Baseline Scheme. This would induce a stronger downwash effect to incoming NNE wind at the north of the Development (Purple Ellipse in Figure 26). The downwash wind would be further directed to the west of the Development along Ching Hiu Road by incoming wind (Blue Arrow in Figure 26). As a result, slightly better VR would be observed at the area.

The stronger downwash effect under Proposed Scheme also limit the incoming wind along channel reaching the east portion of Ching Ho Estate. Hence, slightly lower VR would be observed at the area (Blue Ellipse in Figure 26).

Also, the extended west wing of the residential tower in Proposed Scheme would shield the east portion of Ching Ho Estate Public Transport Interchange (Orange Ellipse in Figure 26). As a result, slightly lower VR would be observed locally at the area.

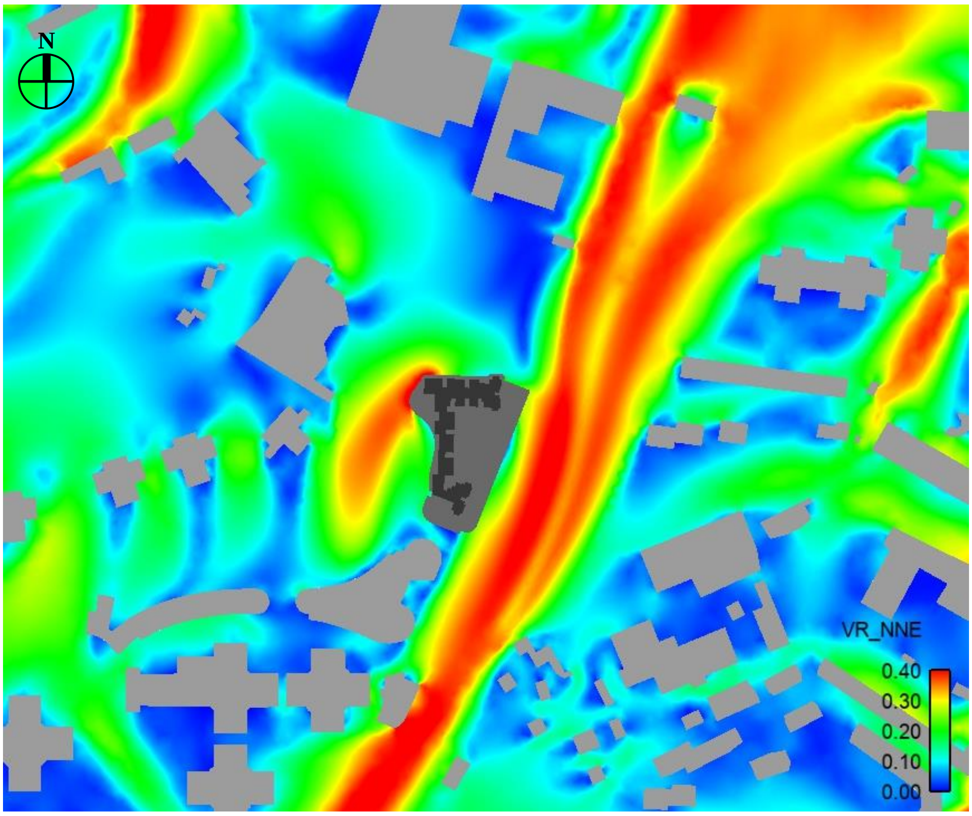


Figure 25 VR Contour Plot of NNE Direction for Baseline Scheme

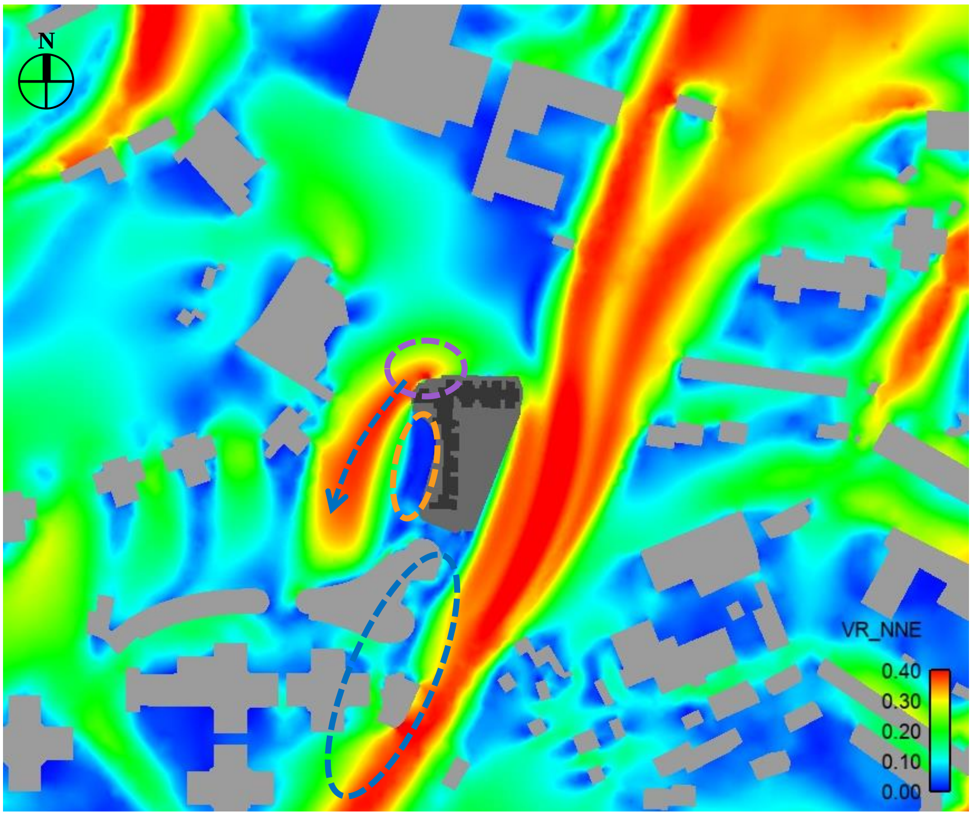


Figure 26 VR Contour Plot of NNE Direction for Proposed Scheme

6.2.2 NE Wind

NE wind contributes approximately 8.2% of the annual wind rose. The VR contour plots Baseline Scheme and Proposed Scheme are shown in Figure 27 and Figure 28 respectively. In general, the overall ventilation environment is similar among the two schemes.

Under Proposed Scheme, the residential tower abuts the podium edge when compared to Baseline Scheme. This would enable most of the downwash wind to reach the pedestrian level (Purple Ellipse in Figure 28). The downwash wind is then distributed along the east side of the Podium along prevailing wind direction (Blue Arrow in Figure 28). As a result, slightly better VR would be observed at the area.

Under Proposed Scheme, west wing of the Development extended further towards the south when compared with Baseline Scheme. This would shield the east portion of Ching Ho Estate Public Transport Interchange (Orange Ellipse in Figure 28). As a result, slightly lower VR would be observed at the area.

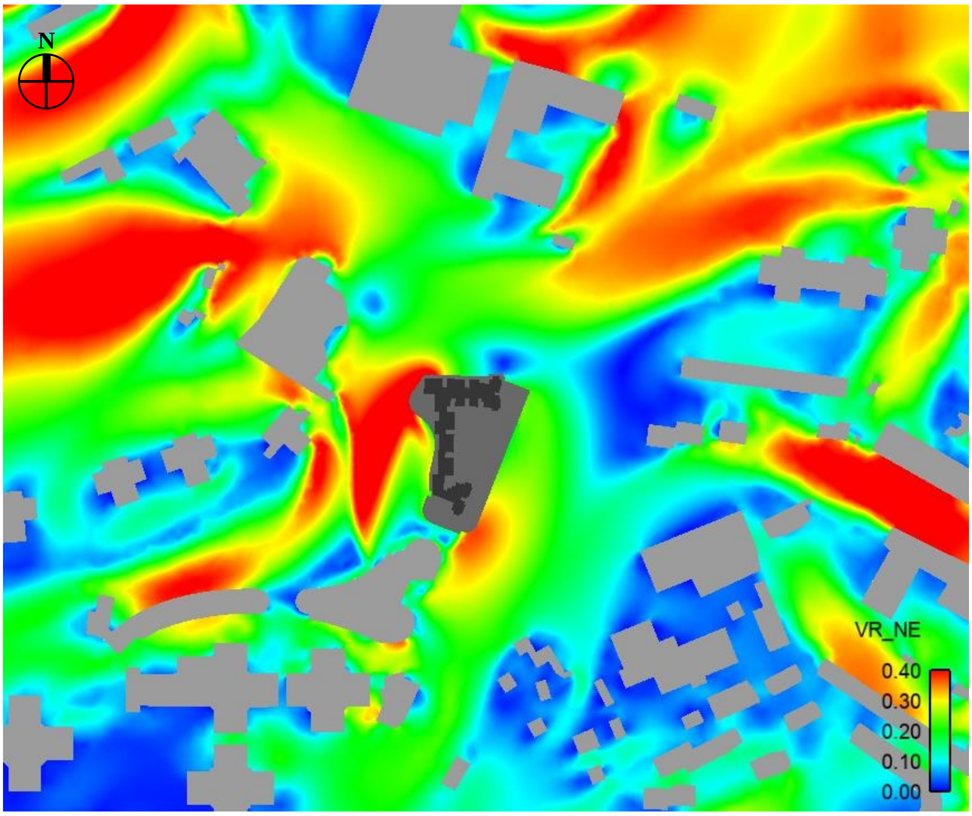


Figure 27 VR Contour Plot of NE Direction for Baseline Scheme

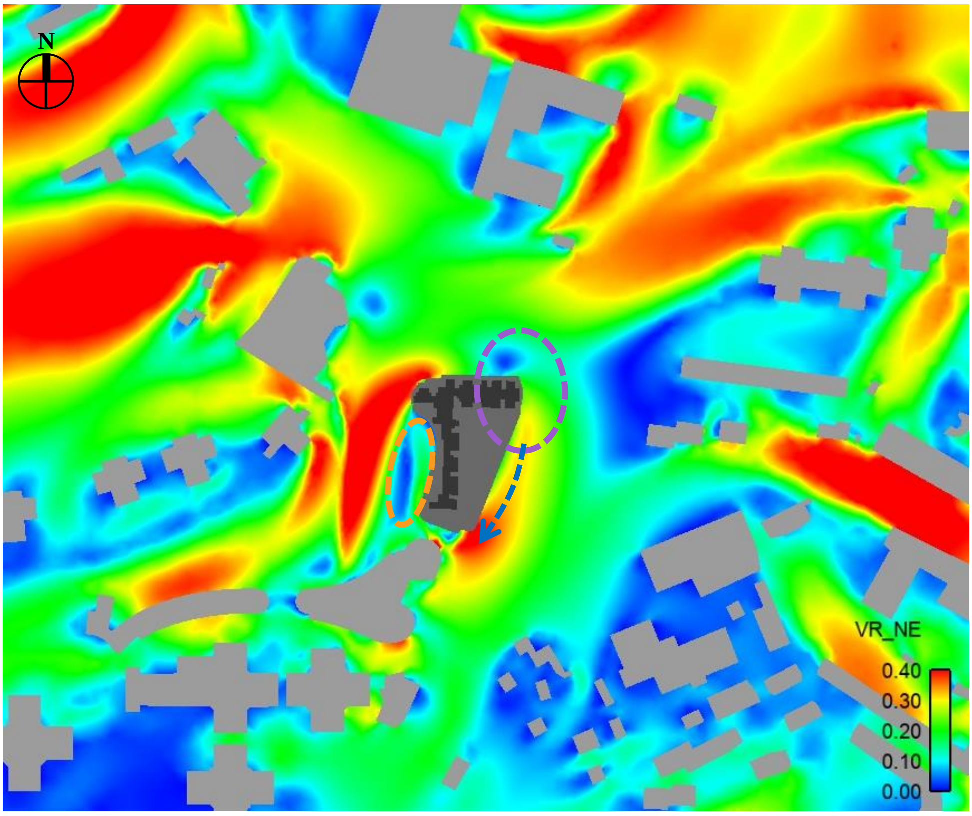


Figure 28 VR Contour Plot of NE Direction for Proposed Scheme

6.2.3 ENE & E Wind

ENE wind contributes approximately 10.2% of the annual wind rose. The VR contour plots Baseline Scheme and Proposed Scheme are shown in Figure 29 and Figure 30 respectively.

E wind contributes approximately 17.2% of the annual wind rose and 7.3% of the summer wind rose. The VR contour plots Baseline Scheme and Proposed Scheme are shown in Figure 31 and Figure 32 respectively.

In general, the overall ventilation environment is similar among the two schemes. The prevailing wind would skim over the low-rise villages and reach the site from the east site boundary. Baseline Scheme has better ventilation performance at 8 Royal Green and Ching Ho Estate Public Transport Interchange, while Proposed Scheme has better ventilation performance at Royal Green.

Under Proposed Scheme, residential tower abuts the podium edge at the northeast corner while there is residential tower setback from podium under Baseline Scheme. The alignment of the edges of tower and podium would enable most of the downwash wind to reach the pedestrian level and disturb the wind environment at the east of the Development, where shielded by mid-rise Eden Garden and Vienna Garden (Purple Ellipse in Figure 30 and Figure 32). As a result, slightly better VR would be observed at the area.

Under Baseline Scheme, the incoming wind would flow along the northern edge of the podium to reach the leeward side of the Development (Blue Arrows in Figure 29 and Figure 31). Under Proposed Scheme, the alignment of the residential tower and podium edge at the northeast corner of the Development would facilitate the downwash of incoming wind to pedestrian level as mentioned above. This would disrupt the wind flow towards the leeward side of the Development. As a result, slightly lower VR could be observed at the region to the east of the Development under Proposed Scheme.

Under Proposed Scheme, the podium extends towards the Ching Ho Shopping Centre narrowing the building separation between and causes wind tunnel effect (Orange Ellipse in Figure 30 and Figure 32). As a result, slightly higher VR would be observed at the south of the Development under Proposed Scheme.

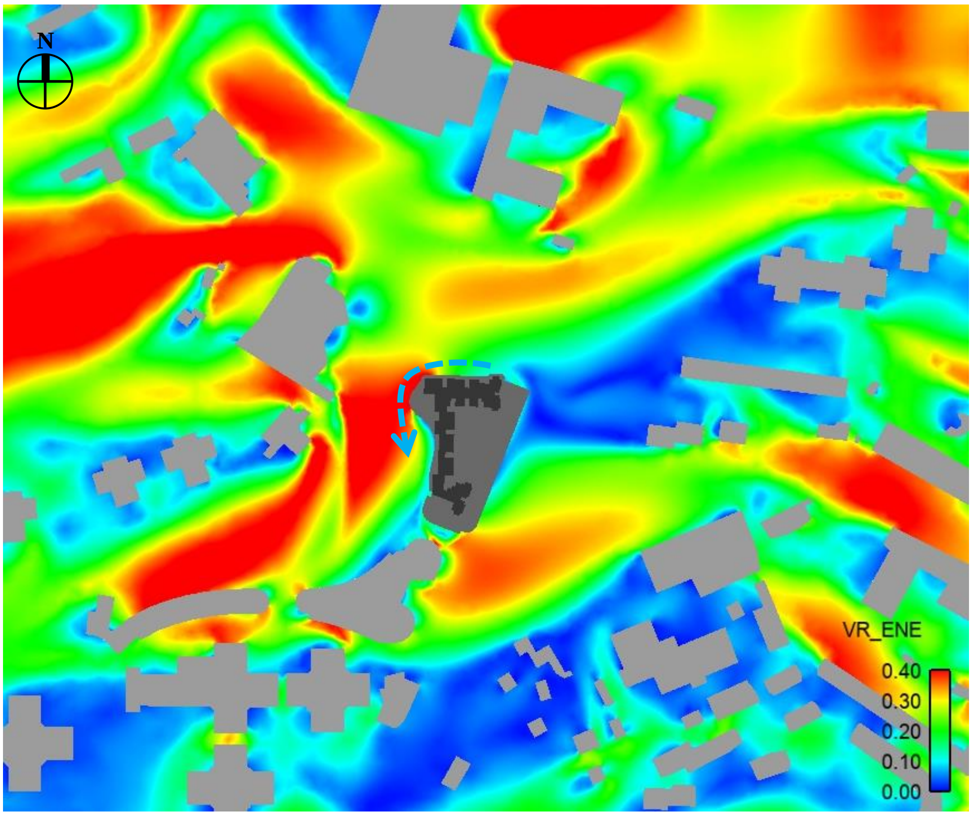


Figure 29 VR Contour Plot of ENE Direction for Baseline Scheme

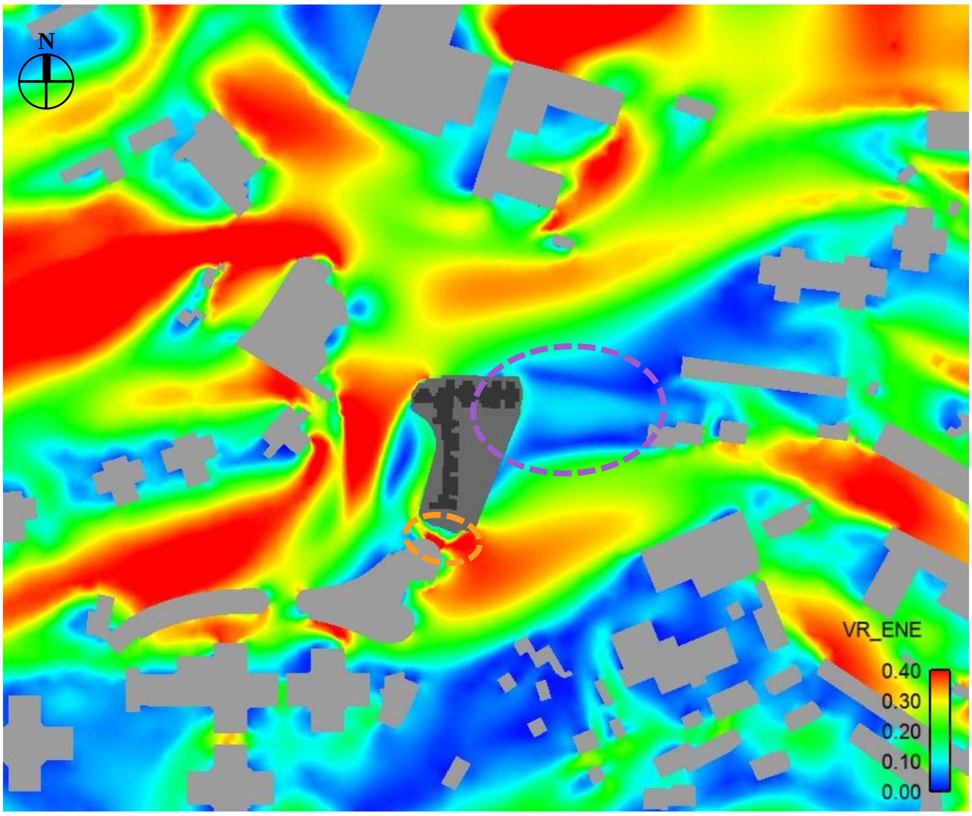


Figure 30 VR Contour Plot of ENE Direction for Proposed Scheme

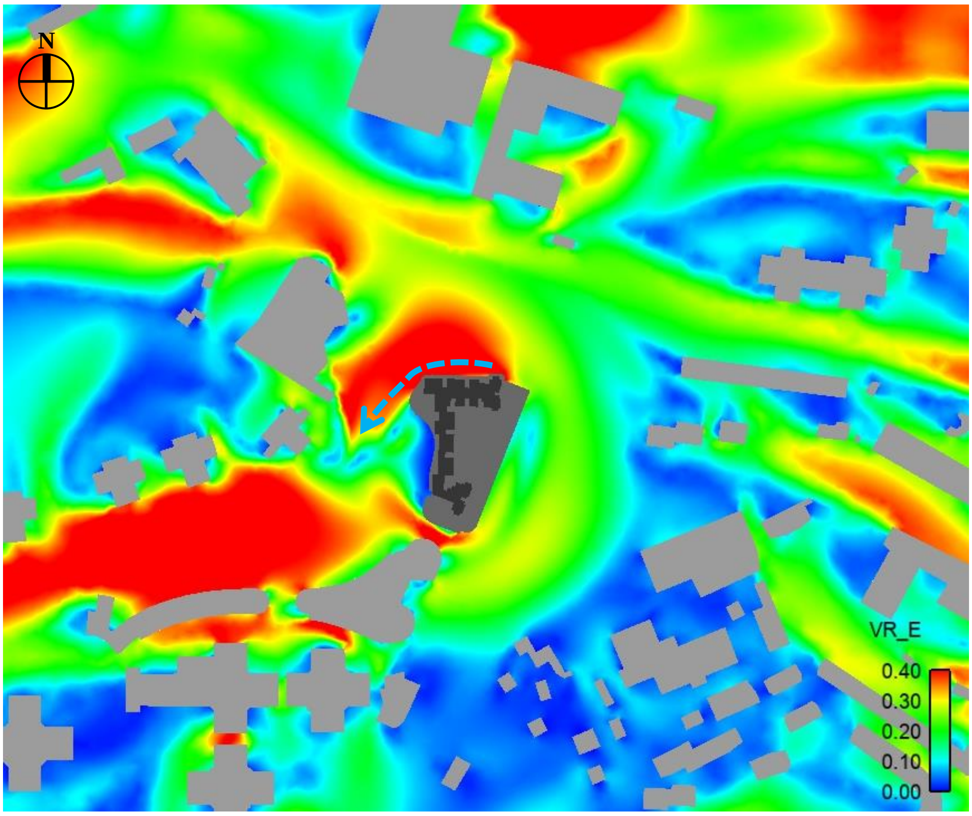


Figure 31 VR Contour Plot of E Direction for Baseline Scheme

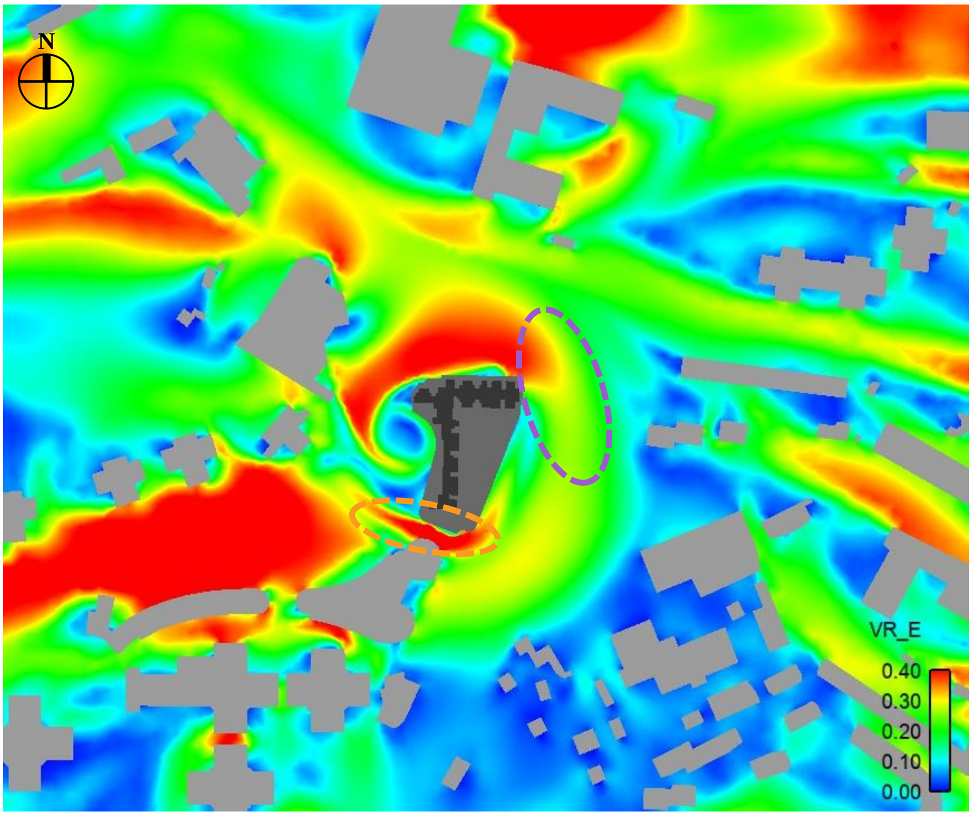


Figure 32 VR Contour Plot of E Direction for Proposed Scheme

6.2.4 ESE Wind

ESE wind contributes approximately 14.7% of the annual wind rose and 10.3% of the summer wind rose. The VR contour plots Baseline Scheme and Proposed Scheme are shown in Figure 33 and Figure 34 respectively. In general, the overall ventilation environment is similar among the two schemes.

Under Proposed Scheme, stronger downwash wind at pedestrian level would be observed at the northeast corner of the Development due to the alignment of the edges of residential tower and podium (Blue Ellipse in Figure 33). The downwash wind would slightly disturb the wind flow at the northwest region, and a slightly less amount of the wind would be penetrate to the leeward side of the Development (Purple Ellipse in Figure 33).

Under Baseline Scheme, the building setback at the south side of the Development is slightly larger when compared to Proposed Scheme. This enables ESE wind to penetrate through more effectively and enhance the ventilation performance at Ching Ho Estate Public Transport Interchange and Ching Hiu Road (Orange Ellipse in Figure 33).

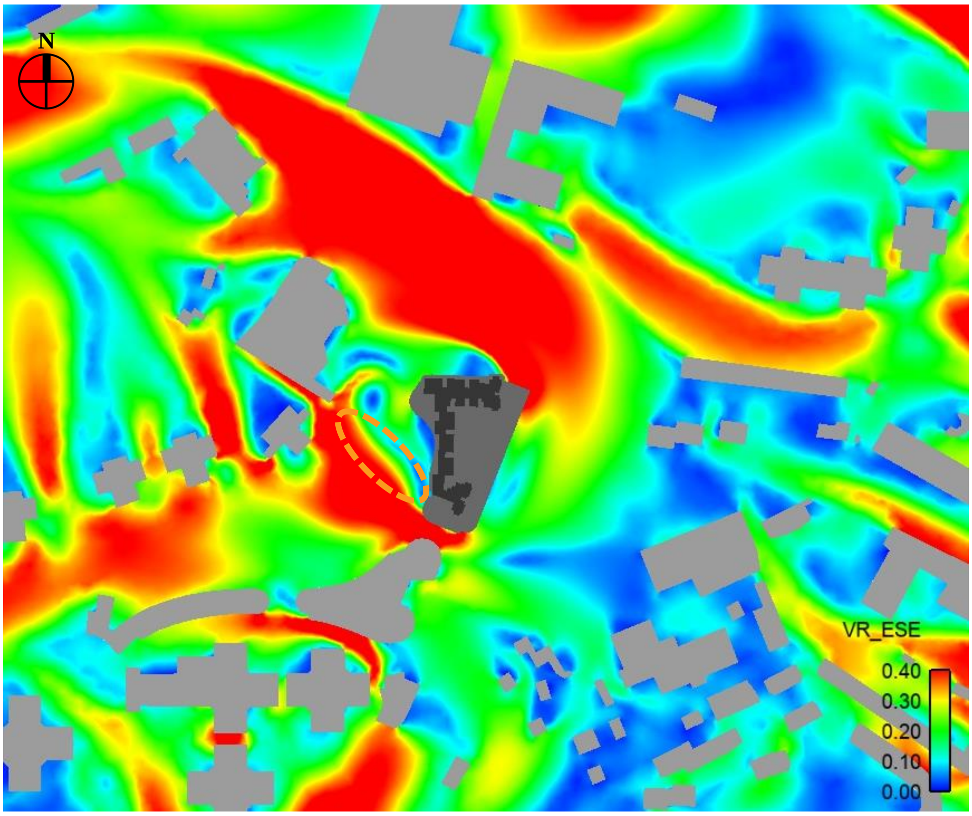


Figure 33 VR Contour Plot of ESE Direction for Baseline Scheme

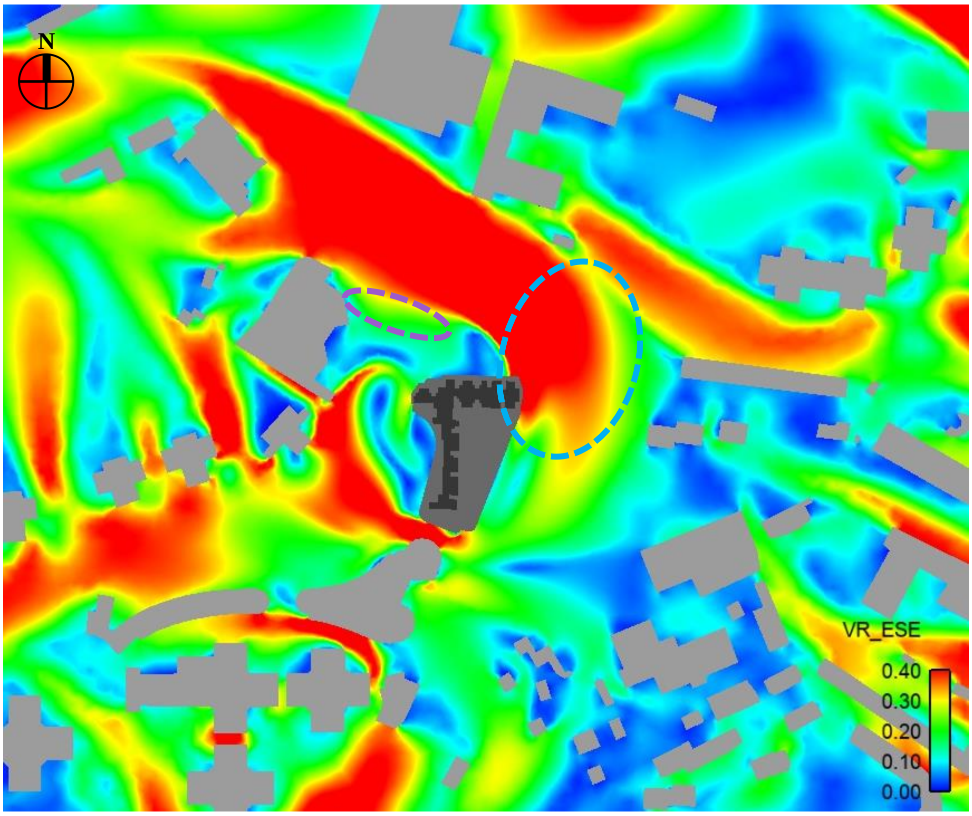


Figure 34 VR Contour Plot of ESE Direction for Proposed Scheme

6.2.5 SE & SSE Wind

SE wind contributes approximately 8.6% of the annual wind rose and 8.9% of the summer wind rose. The VR contour plots Baseline Scheme and Proposed Scheme are shown in Figure 35 and Figure 36 respectively.

SSE wind contributes approximately 8.9% of the summer wind rose. The VR contour plots Baseline Scheme and Proposed Scheme are shown in Figure 37 and Figure 38 respectively.

In general, the overall ventilation environment is similar among the two schemes. Baseline Scheme would result better ventilation performance at 8 Royal Green, while Proposed Scheme would result better ventilation performance at Ching Ho Estate Public Transport Interchange and Pak Wo Road.

The prevailing wind would skim over the low-rise villages and reach the Development from southeast boundary. Proposed Scheme has 4/F podium with higher permeability when compared to Baseline Scheme. The incoming wind would penetrate through the 4/F podium more effectively and arrive at Ching Ho Estate Public Transport Interchange (Orange Ellipse in Figure 36 and Figure 38). Slightly better VR be observed at the area under Proposed Scheme.

The alignment of building façade perpendicular to the south under Proposed Scheme would direct the incoming wind towards to the west along Ching Hiu Road, which reduces the counterflow from the downwash wind of Glorious Peak. Hence, better VR would be observed at the area (Green Ellipse in Figure 36 and Figure 38).

Proposed Scheme aligned the edges of residential tower and podium, which allows more downwash wind to reach the pedestrian level and reach Wai Hong Road Garden when compared to Baseline Scheme. The downwash wind is then distributed along Pak Wo Road, better VR would be observed at the area (Blue Ellipse in Figure 36 and Figure 38).

Under Baseline Scheme, a portion of the incoming wind would skim over the Ching Ho Shopping Centre at the south of the Development and penetrate towards 8 Royal Green. The wind would then be diverted towards the pedestrian level, where slightly higher VR would be observed (Purple Ellipses in Figure 35 and Figure 37).

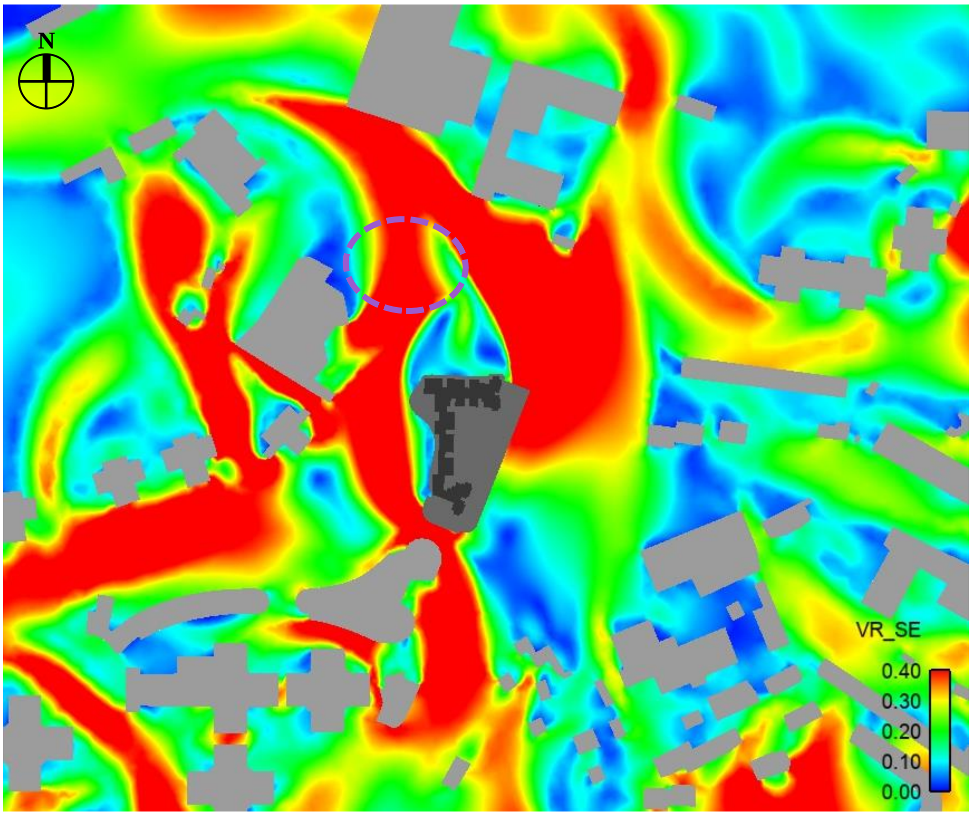


Figure 35 VR Contour Plot of SE Direction for Baseline Scheme

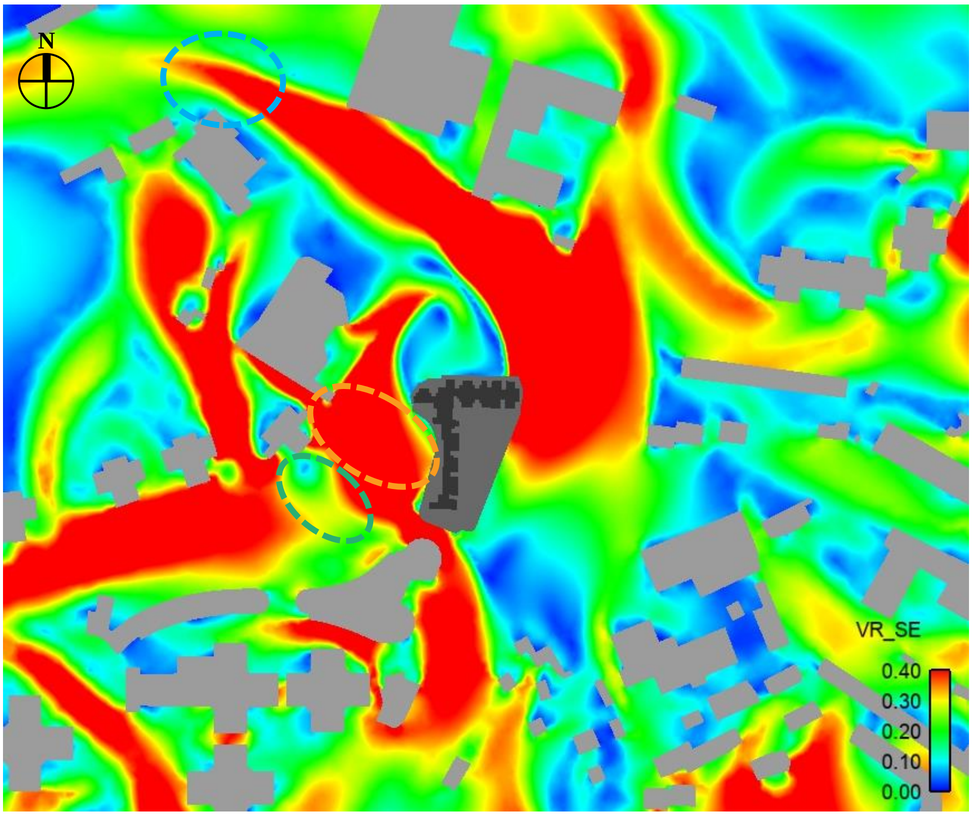


Figure 36 VR Contour Plot of SE Direction for Proposed Scheme

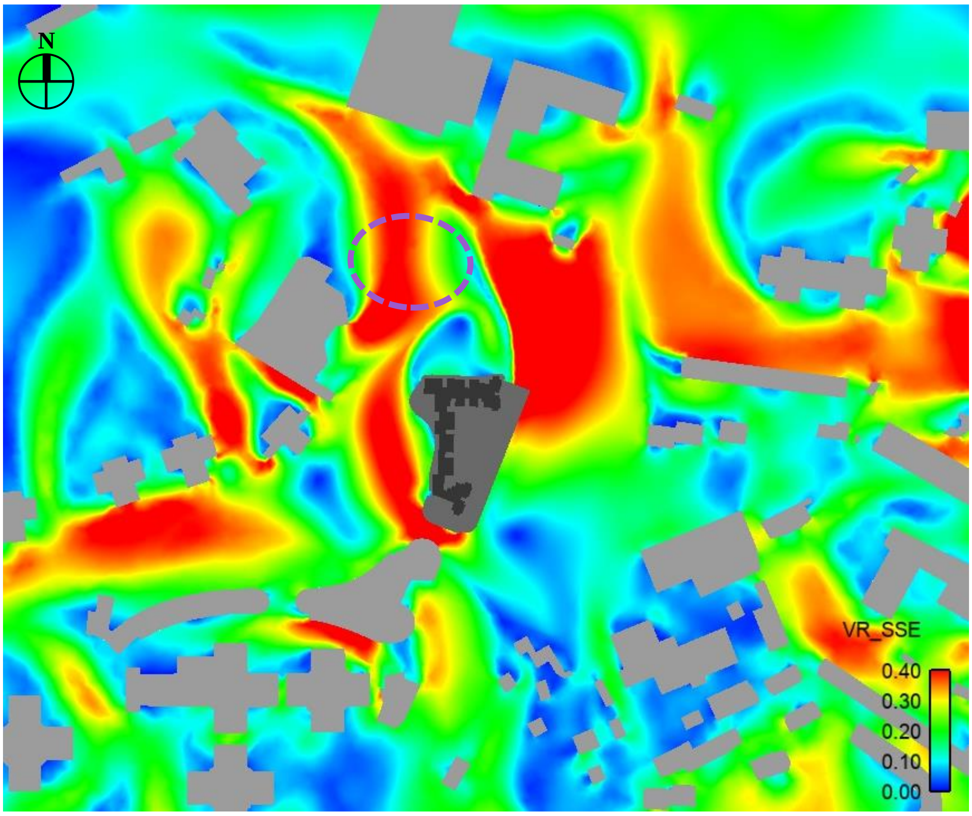


Figure 37 VR Contour Plot of SSE Direction for Baseline Scheme

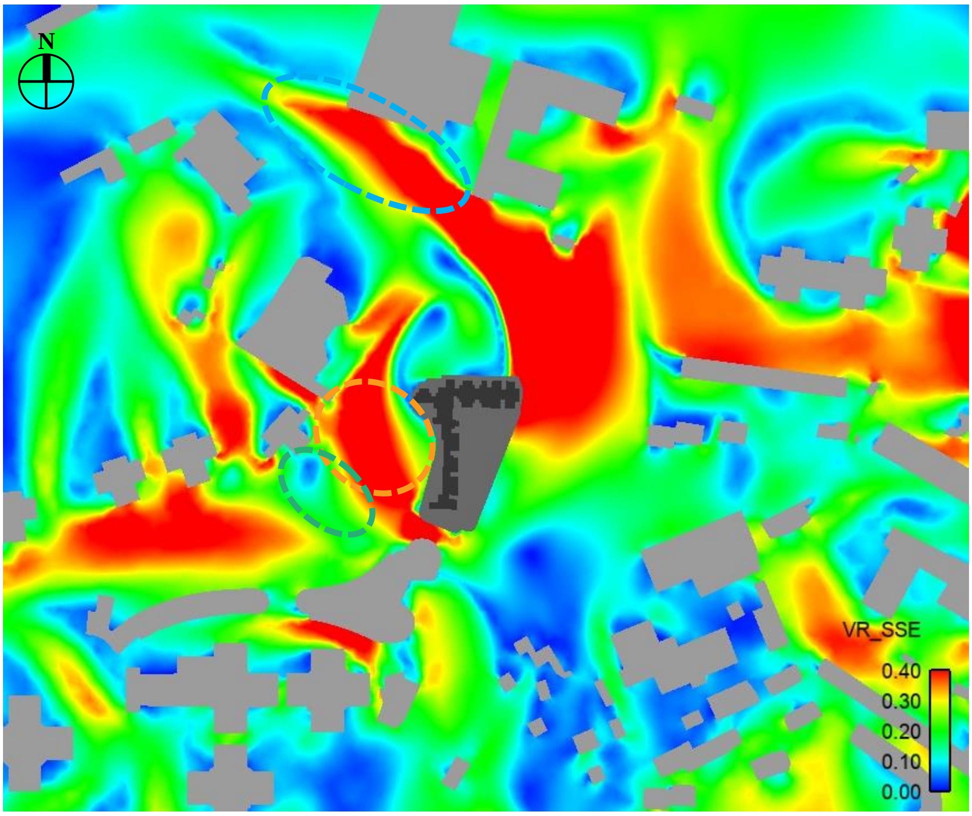


Figure 38 VR Contour Plot of SSE Direction for Proposed Scheme

6.2.6 S Wind

S wind contributes approximately 9.7% of the summer wind rose. The VR contour plots Baseline Scheme and Proposed Scheme are shown in Figure 39 and Figure 40 respectively. In general, the overall ventilation environment is similar among the two schemes.

Under Proposed Scheme, the larger tower frontage facing the south direction would capture a larger amount of the incoming wind and downwash it towards the pedestrian level. Hence a stronger wind stream would be observed at the east side of the development towards the leeward direction (Blue Arrows in Figure 40). Hence, better VR be observed at the area under Proposed Scheme.

Meanwhile, the slightly larger podium frontage under Proposed Scheme would induce larger flow separation that redistributes the a portion of the incoming wind towards northwest direction through Ching Ho Estate Public Transport Interchange to Glorious Peak and 8 Royal Green (**Black Arrows** in Figure 40). Hence, better VR be observed at the areas under Proposed Scheme.

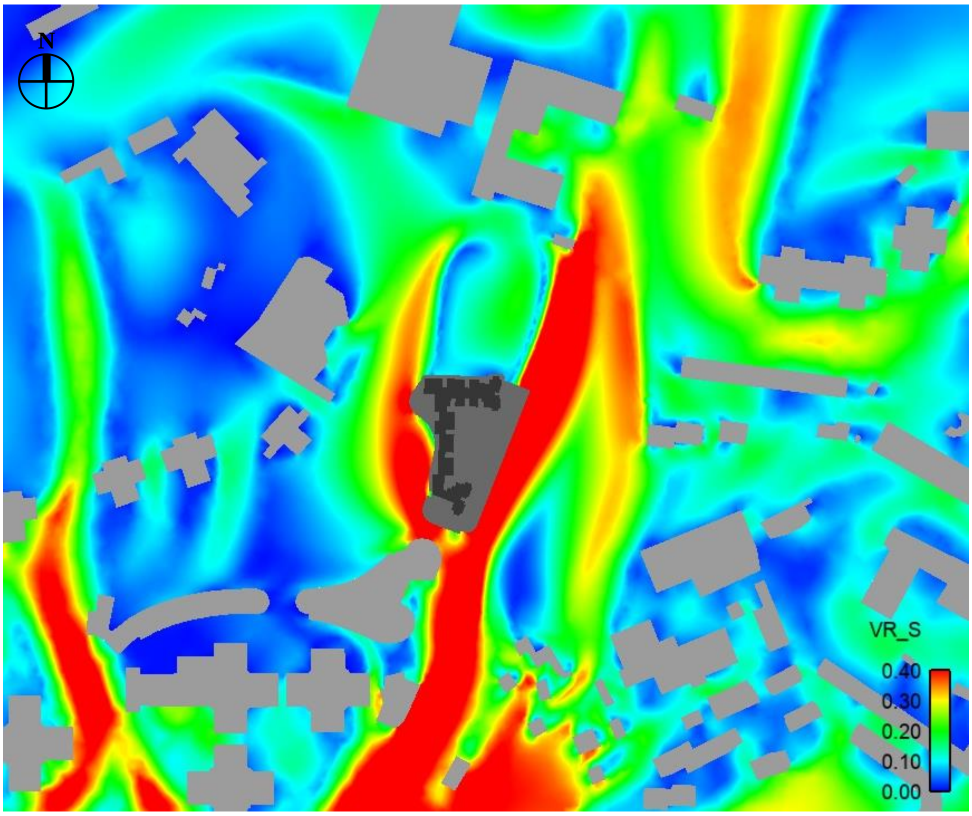


Figure 39 VR Contour Plot of S Direction for Baseline Scheme

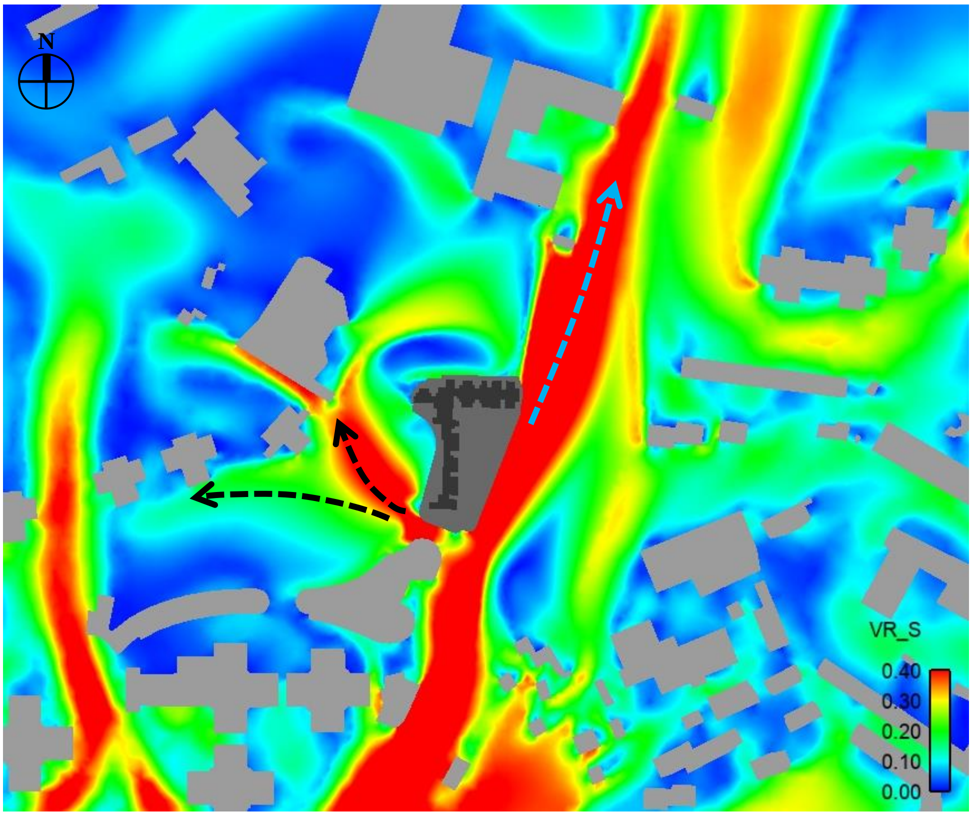


Figure 40 VR Contour Plot of S Direction for Proposed Scheme

6.2.7 SSW Wind

SSW wind contributes approximately 6.5% of the annual wind rose and 14.0% of the summer wind rose. The VR contour plots Baseline Scheme and Proposed Scheme are shown in Figure 41 and Figure 42 respectively. In general, the overall ventilation environment is similar among the two schemes.

A portion of the prevailing wind would approach the south side of the Development. Under Baseline Scheme, the larger tower frontage at the south end of the residential tower would divert a larger amount of the wind towards the region to the northeast of the Development. (Blue Ellipse in Figure 41).

Another portion of the incoming wind would penetrate through the building separations at the existing Ching Ho Estate and be redirected by the mid-rise building clusters at the north of development. Then, the redirected wind would reach the Development from the north site boundary. The larger building frontage under Proposed Scheme would induce a larger stagnant zone at the north of the Development (Purple Ellipse in Figure 42).

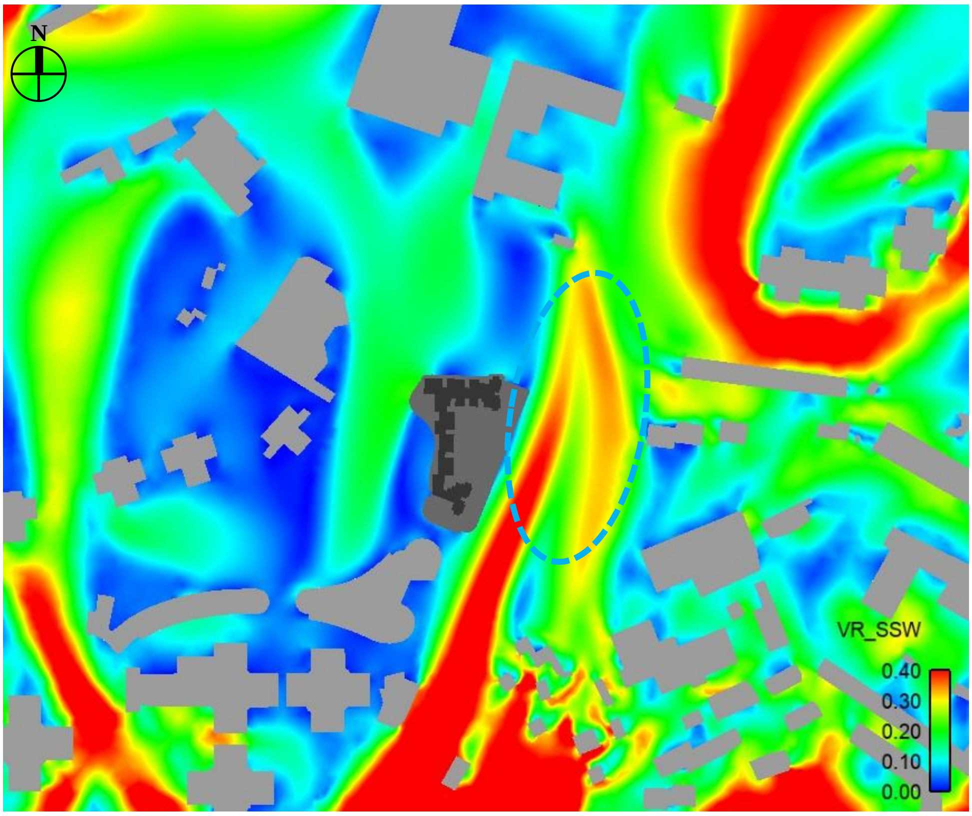


Figure 41 VR Contour Plot of SSW Direction for Baseline Scheme

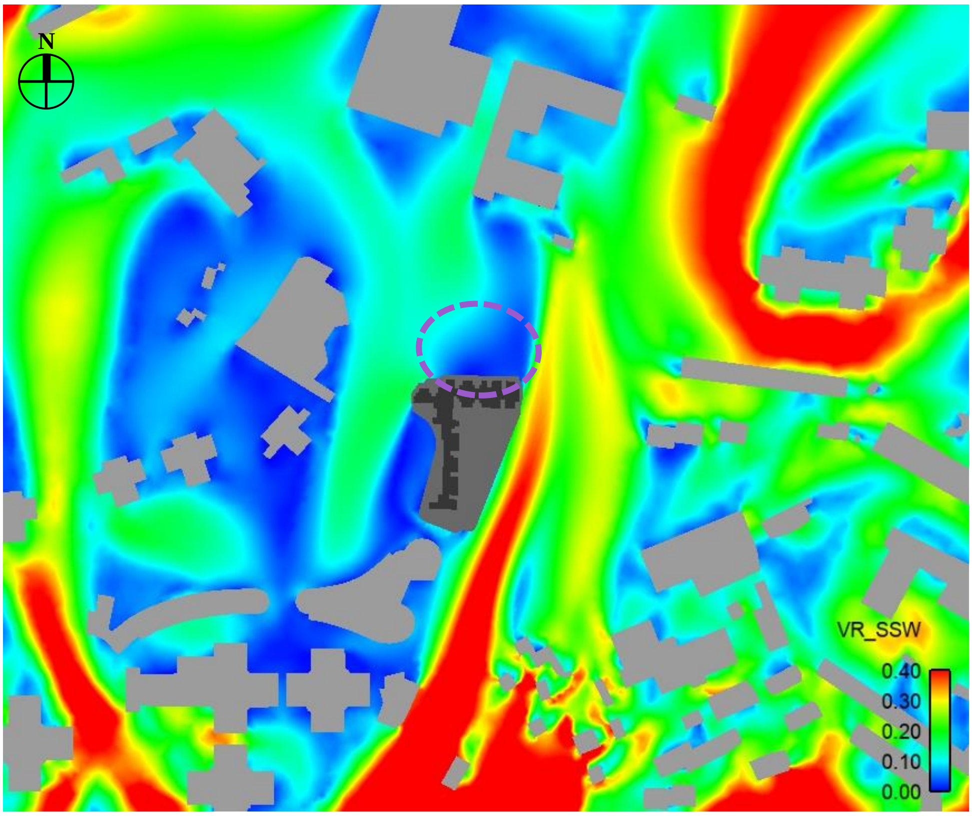


Figure 42 VR Contour Plot of SSW Direction for Proposed Scheme

6.2.8 SW & WSW Wind

SW wind contributes approximately 5.5% of the annual wind rose and 13.0% of the summer wind rose. The VR contour plots Baseline Scheme and Proposed Scheme are shown in Figure 43 and Figure 44 respectively. In general, the overall ventilation environment is similar among the two schemes.

WSW wind contributes approximately 8.9% of the summer wind rose. The VR contour plots Baseline Scheme and Proposed Scheme are shown in Figure 45 and Figure 46 respectively. In general, the overall ventilation environment is similar among the two schemes. Baseline Scheme would result better ventilation performance at Pak Wo Road, Wai Hong Road and Kai Leng Tsuen, while Proposed Scheme would result better ventilation performance at Ching Ho Estate and So Kwun Po Road.

The extended west wing of residential tower under Proposed Scheme would shield the leeward side and result a larger wake zone when compare to Baseline Scheme. Under SW wind, the incoming wind would be redirected and disturb the wind environment at 8 Royal Green in Proposed Scheme and results better VR (Orange Ellipse in Figure 44). Under WSW wind, a portion of Pak Wo Road will be shielded by the Development. Hence, lower VR would be observed at the area under Proposed Scheme (Orange Ellipse in Figure 46).

The extended podium at the south of the Development would narrows the separation between the Development and Ching Ho Shopping Centre for incoming wind to penetrate through. Hence, slightly lower VR would be observed at leeward side of the Development under Proposed Scheme, which are Wai Hong Road and Kai Leng Tsuen under WSW wind (Purple Ellipses in Figure 44 and Figure 46).

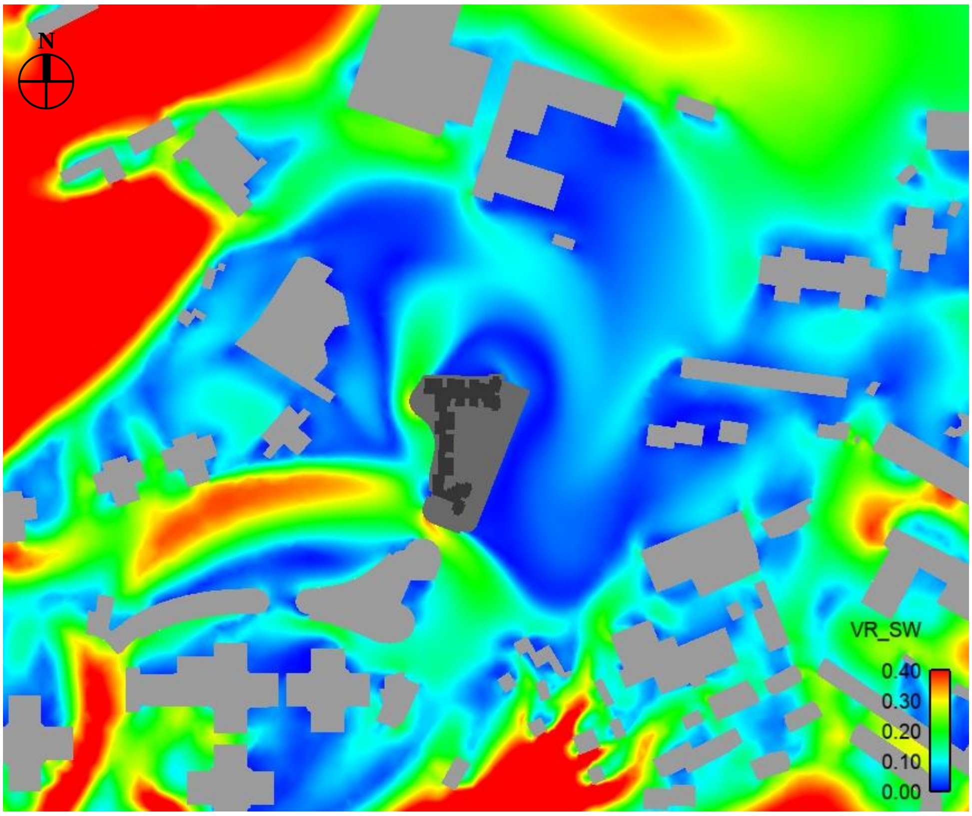


Figure 43 VR Contour Plot of SW Direction for Baseline Scheme

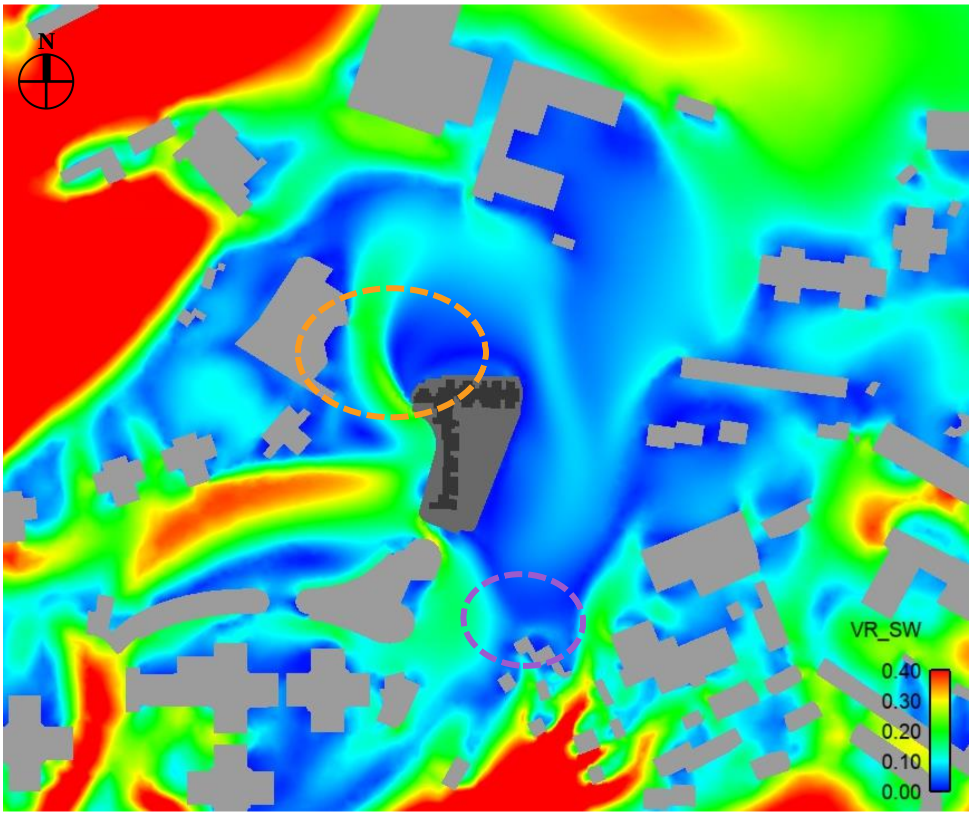


Figure 44 VR Contour Plot of SW Direction for Proposed Scheme

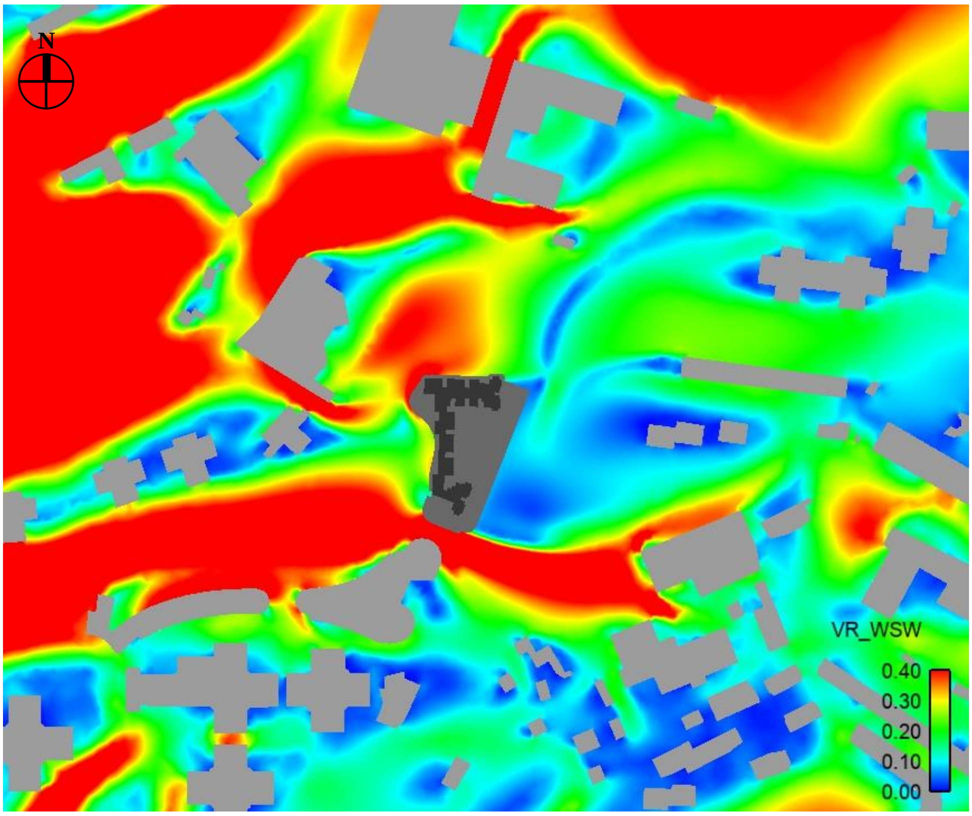


Figure 45 VR Contour Plot of WSW Direction for Baseline Scheme

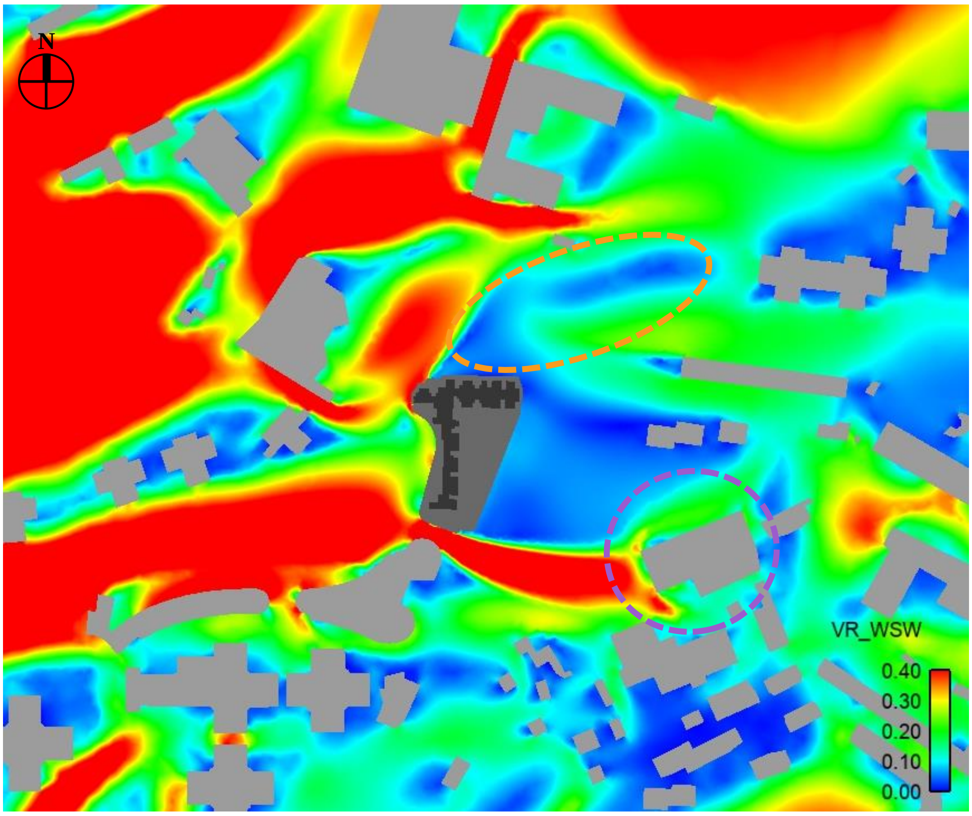


Figure 46 VR Contour Plot of WSW Direction for Proposed Scheme

6.3 Focus Area

Various Focus Areas with frequent pedestrian access and within major activity zones were defined, as shown in Figure 47.

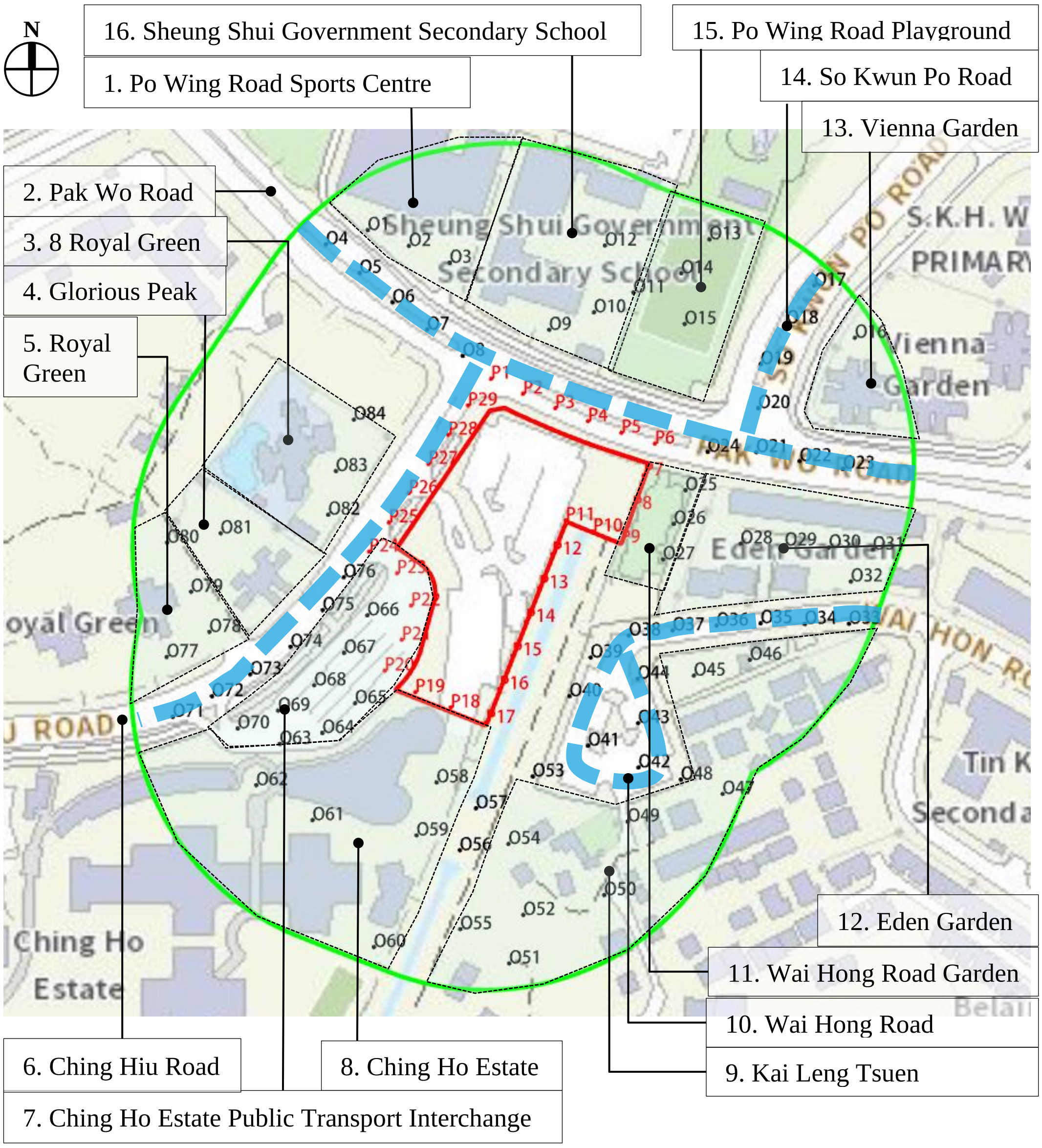


Figure 47 Location of Focus Areas

6.3.1 Annual Condition

Table 7 VR Results for Focus Areas under Annual Wind Condition

	Focus Areas	Test Points	Baseline Scheme	Proposed Scheme
1	Po Wing Road Sports Centre	O1-O3	0.19	0.19
2	Pak Wo Road	O4-O8, O21-O24, P1-P6	0.26	0.27
3	8 Royal Green	O82-O84	0.19	0.18
4	Glorious Peak	O74-O76, O81	0.25	0.27
5	Royal Green	O77 – O80	0.25	0.26
6	Ching Hiu Road	O71-O76, P24-P29, P1	0.28	0.28
7	Ching Ho Estate Public Transport Interchange	O63-O70, P20-P23	0.24	0.23
8	Ching Ho Estate	O58-O62	0.21	0.21
9	Kai Leng Tsuen	O45 – O57	0.15	0.15
10	Wai Hong Road	O33 - O44	0.17	0.17
11	Wai Hong Road Garden	P7-P9, O25 - O27	0.19	0.20
12	Eden Garden	O28 - O32	0.11	0.11
13	Vienna Garden	O16 - O23	0.20	0.20
14	So Kwun Po Road	O17 - O20	0.21	0.21
15	Po Wing Road Playground	O13 – O14	0.19	0.19
16	Sheung Shui Government Secondary School	O9-O12	0.19	0.20

Under annual condition, the two schemes would achieve similar VR (within ±0.01) at most of the focus areas, indicating their ventilation performance is quite similar in general.

Slightly higher VR would be observed at Glorious Peak under Proposed Scheme. It is mainly because of the stronger downwash effect to pedestrian level induced by the alignment of residential tower and podium, and permeable podium design under Proposed Scheme.

6.3.2 Summer Condition

Table 8 VR Results for Focus Areas under Summer Wind Condition

	Focus Areas	Test Points	Baseline Scheme	Proposed Scheme
1	Po Wing Road Sports Centre	O1-O3	0.22	0.22
2	Pak Wo Road	O4-O8, O21-O24, P1-P6	0.26	0.26
3	8 Royal Green	O82-O84	0.15	0.15
4	Glorious Peak	O74-O76, O81	0.18	0.23
5	Royal Green	O77 – O80	0.23	0.24
6	Ching Hiu Road	O71-O76, P24-P29, P1	0.24	0.24
7	Ching Ho Estate Public Transport Interchange	O63-O70, P20-P23	0.22	0.23
8	Ching Ho Estate	O58-O62	0.18	0.19
9	Kai Leng Tsuen	O45 – O57	0.19	0.19
10	Wai Hong Road	O33 - O44	0.15	0.15
11	Wai Hong Road Garden	P7-P9, O25 - O27	0.23	0.24
12	Eden Garden	O28 - O32	0.12	0.12
13	Vienna Garden	O16 - O23	0.22	0.22
14	So Kwun Po Road	O17 - O20	0.22	0.22
15	Po Wing Road Playground	O13 – O14	0.19	0.19
16	Sheung Shui Government Secondary School	O9-O12	0.17	0.18

Under summer condition, the two schemes would achieve similar VR (within ±0.01) at most of the focus areas, indicating their ventilation performance is quite similar in general.

Slightly higher VR would be observed at Glorious Peak under Proposed Scheme. It is mainly because of the stronger downwash effect to pedestrian level induced by the alignment of residential tower perpendicular to incoming wind direction under Proposed Scheme.

7 Conclusion

Ove Arup and Partners Hong Kong Ltd (Arup) was appointed by Hong Kong Housing Authority (HKHA) to carry out an Air Ventilation Assessment Initial Study for Proposed Public Housing Development at Fanling Area 36 Phase 4 (the Development).

A series of Computational Fluid Dynamics (CFD) simulations are performed based on the AVA methodology. Eleven wind directions in total, which cover 77.3% and 81.0% of annual and summer wind condition of the area respectively, have been considered. The ventilation performance for the Development at the site boundary and within the assessment area was assessed under Baseline Scheme and Proposed Scheme.

Under annual condition and summer condition, Proposed Scheme could achieve a slightly higher SVR than Baseline Scheme and a same LVR with Baseline Scheme. The result shows that the overall ventilation performance in surrounding areas are similar for both schemes.

Major findings of the study could be summarised as below:

Annual condition

- The values of SVR and LVR are same under two schemes, indicating that the ventilation performance of the three scenarios at the immediate area and local surrounding would be generally similar.
- The two schemes would achieve similar VR (within ±0.01) at most of the focus areas. Slightly higher VR would be observed at Glorious Peak under Proposed Scheme.
- In general, the two studied schemes would result in similar ventilation environment.

Summer Condition

- The values of SVR and LVR are same under two schemes, indicating that the ventilation performance of the three scenarios at the immediate area and local surrounding would be generally similar.
- The two schemes would achieve similar VR (within ±0.01) at most of the focus areas. Slightly higher VR would be observed at Glorious Peak under Proposed Scheme.
- In general, the two studied schemes would result in similar ventilation environment.

Appendix A

Velocity Ratio Table of the Test Points

A1 VR Result for Baseline Scheme

Table A- 1 VR of Perimeter Test Points for Baseline Scheme

	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	Combined Annual	Combined Summer
Freq. Annual	6.4%	8.2%	10.2%	17.2%	14.7%	8.6%			6.5%	5.5%		**77.3%**	
Freq. Summer				7.3%	10.3%	8.9%	8.9%	9.7%	14.0%	13.0%	8.9%		**81.0%**
P1	0.06	0.21	0.29	0.23	0.47	0.48	0.17	0.09	0.10	0.09	0.28	**0.27**	**0.23**
P2	0.02	0.25	0.33	0.22	0.47	0.56	0.42	0.16	0.04	0.10	0.28	**0.28**	**0.26**
P3	0.02	0.28	0.33	0.20	0.45	0.57	0.47	0.16	0.05	0.10	0.20	**0.28**	**0.25**
P4	0.25	0.29	0.30	0.18	0.41	0.54	0.46	0.54	0.23	0.09	0.07	**0.30**	**0.31**
P5	0.35	0.27	0.24	0.16	0.34	0.50	0.42	0.40	0.34	0.07	0.14	**0.28**	**0.29**
P6	0.35	0.20	0.15	0.15	0.24	0.41	0.32	0.36	0.20	0.06	0.20	**0.21**	**0.23**
P7	0.34	0.07	0.09	0.15	0.29	0.43	0.36	0.33	0.32	0.07	0.20	**0.21**	**0.26**
P8	0.33	0.05	0.04	0.14	0.31	0.43	0.37	0.29	0.33	0.08	0.09	**0.21**	**0.25**
P9	0.32	0.08	0.06	0.19	0.32	0.42	0.35	0.26	0.29	0.08	0.09	**0.22**	**0.24**
P10	0.39	0.13	0.03	0.24	0.34	0.51	0.42	0.44	0.33	0.05	0.12	**0.26**	**0.30**
P11	0.27	0.16	0.05	0.25	0.39	0.60	0.47	0.54	0.20	0.02	0.05	**0.26**	**0.30**
P12	0.29	0.23	0.03	0.14	0.35	0.53	0.40	0.53	0.17	0.02	0.08	**0.22**	**0.26**
P13	0.25	0.22	0.06	0.14	0.24	0.41	0.31	0.50	0.16	0.01	0.09	**0.19**	**0.22**
P14	0.20	0.24	0.10	0.22	0.15	0.29	0.22	0.48	0.17	0.01	0.07	**0.18**	**0.19**
P15	0.24	0.29	0.16	0.26	0.10	0.15	0.13	0.47	0.20	0.01	0.05	**0.18**	**0.16**
P16	0.28	0.35	0.27	0.29	0.20	0.10	0.11	0.47	0.23	0.01	0.05	**0.23**	**0.18**
P17	0.30	0.34	0.36	0.25	0.22	0.09	0.21	0.44	0.25	0.20	0.57	**0.25**	**0.27**
P18	0.09	0.04	0.23	0.38	0.43	0.55	0.39	0.32	0.06	0.28	0.63	**0.30**	**0.36**
P19	0.06	0.05	0.09	0.36	0.51	0.59	0.46	0.40	0.04	0.20	0.48	**0.28**	**0.35**
P20	0.18	0.21	0.20	0.33	0.45	0.45	0.34	0.27	0.05	0.22	0.40	**0.29**	**0.29**
P21	0.18	0.21	0.25	0.18	0.29	0.49	0.42	0.42	0.01	0.20	0.26	**0.23**	**0.27**
P22	0.22	0.25	0.29	0.08	0.09	0.30	0.33	0.44	0.03	0.11	0.21	**0.16**	**0.19**
P23	0.32	0.40	0.37	0.09	0.19	0.42	0.36	0.37	0.15	0.09	0.09	**0.24**	**0.21**
P24	0.33	0.41	0.41	0.35	0.08	0.56	0.40	0.28	0.19	0.06	0.32	**0.30**	**0.26**
P25	0.31	0.39	0.37	0.38	0.23	0.47	0.36	0.34	0.20	0.09	0.31	**0.32**	**0.28**
P26	0.26	0.31	0.32	0.43	0.16	0.14	0.21	0.35	0.17	0.17	0.36	**0.27**	**0.24**
P27	0.18	0.22	0.29	0.42	0.30	0.09	0.15	0.26	0.15	0.16	0.37	**0.26**	**0.23**
P28	0.11	0.22	0.31	0.35	0.42	0.10	0.30	0.06	0.16	0.12	0.37	**0.26**	**0.22**
P29	0.07	0.23	0.32	0.28	0.42	0.18	0.21	0.10	0.16	0.10	0.33	**0.26**	**0.21**

Table A- 2 VR of Overall Test Points for Baseline Scheme

	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	Combined Annual	Combined Summer
Freq. Annual	6.4%	8.2%	10.2%	17.2%	14.7%	8.6%			6.5%	5.5%		**77.3%**	
Freq. Summer				7.3%	10.3%	8.9%	8.9%	9.7%	14.0%	13.0%	8.9%		**81.0%**
O1	0.12	0.21	0.29	0.05	0.39	0.44	0.32	0.15	0.04	0.23	0.28	**0.23**	**0.23**
O2	0.09	0.19	0.23	0.06	0.30	0.49	0.27	0.09	0.05	0.22	0.37	**0.21**	**0.22**
O3	0.07	0.16	0.14	0.06	0.17	0.38	0.31	0.08	0.12	0.18	0.39	**0.15**	**0.20**
O4	0.15	0.27	0.35	0.18	0.47	0.34	0.29	0.14	0.16	0.17	0.36	**0.28**	**0.26**
O5	0.14	0.26	0.29	0.21	0.50	0.38	0.36	0.15	0.12	0.11	0.48	**0.28**	**0.27**
O6	0.13	0.25	0.25	0.28	0.52	0.44	0.40	0.15	0.10	0.04	0.56	**0.29**	**0.29**
O7	0.11	0.20	0.26	0.32	0.52	0.34	0.32	0.17	0.15	0.03	0.37	**0.29**	**0.26**
O8	0.08	0.14	0.24	0.31	0.50	0.43	0.17	0.20	0.17	0.06	0.18	**0.28**	**0.24**
O9	0.02	0.10	0.17	0.16	0.22	0.37	0.30	0.10	0.08	0.06	0.40	**0.16**	**0.19**
O10	0.07	0.29	0.35	0.28	0.26	0.21	0.25	0.17	0.14	0.01	0.25	**0.23**	**0.18**
O11	0.31	0.38	0.36	0.27	0.14	0.32	0.21	0.34	0.12	0.03	0.17	**0.25**	**0.19**
O12	0.08	0.12	0.16	0.22	0.16	0.06	0.26	0.19	0.08	0.03	0.10	**0.14**	**0.13**
O13	0.25	0.22	0.21	0.14	0.07	0.26	0.33	0.21	0.27	0.09	0.18	**0.17**	**0.19**
O14	0.36	0.30	0.29	0.20	0.07	0.31	0.25	0.20	0.22	0.04	0.22	**0.21**	**0.18**
O15	0.31	0.34	0.26	0.09	0.10	0.33	0.31	0.22	0.24	0.05	0.16	**0.19**	**0.18**
O16	0.17	0.33	0.17	0.11	0.10	0.08	0.11	0.05	0.08	0.09	0.09	**0.14**	**0.09**
O17	0.33	0.32	0.25	0.10	0.12	0.14	0.10	0.28	0.37	0.16	0.22	**0.20**	**0.20**
O18	0.33	0.38	0.29	0.06	0.13	0.08	0.10	0.33	0.42	0.13	0.05	**0.20**	**0.18**
O19	0.32	0.36	0.26	0.09	0.09	0.24	0.33	0.30	0.41	0.10	0.12	**0.20**	**0.22**
O20	0.27	0.15	0.08	0.23	0.35	0.36	0.35	0.25	0.36	0.10	0.17	**0.24**	**0.27**
O21	0.19	0.09	0.04	0.22	0.36	0.28	0.36	0.16	0.28	0.08	0.24	**0.21**	**0.24**
O22	0.04	0.11	0.04	0.22	0.37	0.30	0.36	0.20	0.39	0.08	0.24	**0.21**	**0.27**
O23	0.08	0.09	0.05	0.22	0.38	0.28	0.35	0.28	0.51	0.08	0.23	**0.22**	**0.30**
O24	0.32	0.02	0.06	0.19	0.31	0.16	0.34	0.14	0.23	0.08	0.23	**0.18**	**0.21**
O25	0.33	0.03	0.03	0.10	0.20	0.30	0.18	0.23	0.18	0.08	0.10	**0.15**	**0.17**
O26	0.32	0.02	0.04	0.11	0.21	0.33	0.27	0.35	0.21	0.09	0.13	**0.16**	**0.21**
O27	0.31	0.02	0.05	0.10	0.22	0.34	0.28	0.34	0.30	0.09	0.03	**0.17**	**0.22**
O28	0.13	0.03	0.05	0.04	0.04	0.06	0.20	0.18	0.29	0.02	0.11	**0.07**	**0.12**
O29	0.16	0.09	0.08	0.09	0.06	0.10	0.17	0.16	0.28	0.02	0.14	**0.10**	**0.13**
O30	0.08	0.21	0.16	0.18	0.11	0.11	0.14	0.08	0.19	0.06	0.16	**0.14**	**0.13**
O31	0.07	0.07	0.06	0.05	0.04	0.08	0.13	0.07	0.11	0.06	0.15	**0.06**	**0.09**
O32	0.08	0.33	0.28	0.25	0.07	0.17	0.14	0.13	0.13	0.09	0.15	**0.18**	**0.13**
O33	0.21	0.31	0.32	0.23	0.20	0.20	0.15	0.12	0.20	0.08	0.22	**0.23**	**0.17**
O34	0.17	0.18	0.24	0.11	0.11	0.11	0.08	0.16	0.14	0.10	0.19	**0.14**	**0.12**
O35	0.11	0.16	0.23	0.05	0.04	0.04	0.09	0.12	0.16	0.06	0.11	**0.10**	**0.09**
O36	0.07	0.16	0.25	0.03	0.05	0.11	0.16	0.10	0.05	0.05	0.10	**0.09**	**0.08**

	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	Combined Annual	Combined Summer
O37	0.07	0.11	0.25	0.09	0.14	0.25	0.18	0.28	0.21	0.03	0.10	**0.14**	**0.16**
O38	0.34	0.10	0.26	0.20	0.20	0.26	0.18	0.27	0.32	0.06	0.09	**0.22**	**0.20**
O39	0.34	0.19	0.28	0.26	0.23	0.20	0.14	0.15	0.21	0.05	0.06	**0.23**	**0.16**
O40	0.35	0.22	0.33	0.28	0.18	0.13	0.07	0.09	0.16	0.04	0.10	**0.22**	**0.13**
O41	0.27	0.17	0.31	0.20	0.08	0.11	0.07	0.18	0.24	0.03	0.58	**0.18**	**0.18**
O42	0.08	0.11	0.07	0.04	0.07	0.23	0.13	0.22	0.19	0.13	0.47	**0.10**	**0.18**
O43	0.13	0.14	0.28	0.12	0.05	0.22	0.12	0.28	0.24	0.03	0.44	**0.15**	**0.18**
O44	0.18	0.15	0.32	0.18	0.13	0.23	0.14	0.32	0.31	0.04	0.14	**0.19**	**0.19**
O45	0.10	0.11	0.29	0.08	0.08	0.17	0.16	0.12	0.08	0.05	0.25	**0.12**	**0.12**
O46	0.15	0.08	0.21	0.06	0.04	0.06	0.12	0.12	0.12	0.08	0.29	**0.09**	**0.11**
O47	0.05	0.06	0.05	0.05	0.11	0.11	0.08	0.10	0.14	0.12	0.39	**0.08**	**0.14**
O48	0.08	0.04	0.06	0.04	0.04	0.11	0.09	0.08	0.12	0.11	0.40	**0.07**	**0.12**
O49	0.10	0.10	0.09	0.08	0.16	0.25	0.17	0.22	0.27	0.18	0.21	**0.14**	**0.20**
O50	0.10	0.11	0.03	0.03	0.11	0.15	0.07	0.22	0.26	0.34	0.10	**0.11**	**0.18**
O51	0.11	0.10	0.05	0.06	0.30	0.36	0.20	0.41	0.43	0.32	0.14	**0.19**	**0.30**
O52	0.07	0.04	0.04	0.04	0.23	0.35	0.19	0.34	0.39	0.18	0.13	**0.15**	**0.24**
O53	0.32	0.21	0.31	0.22	0.21	0.04	0.10	0.02	0.11	0.13	0.31	**0.20**	**0.14**
O54	0.30	0.16	0.03	0.09	0.10	0.22	0.12	0.21	0.27	0.09	0.13	**0.14**	**0.16**
O55	0.26	0.19	0.03	0.05	0.08	0.37	0.22	0.40	0.51	0.16	0.16	**0.17**	**0.26**
O56	0.37	0.21	0.09	0.06	0.18	0.48	0.29	0.51	0.46	0.14	0.08	**0.22**	**0.29**
O57	0.37	0.24	0.25	0.17	0.16	0.45	0.24	0.50	0.46	0.15	0.15	**0.26**	**0.29**
O58	0.21	0.27	0.31	0.24	0.22	0.46	0.31	0.35	0.09	0.11	0.03	**0.25**	**0.21**
O59	0.23	0.21	0.19	0.09	0.13	0.23	0.18	0.10	0.05	0.13	0.15	**0.15**	**0.13**
O60	0.36	0.20	0.04	0.13	0.38	0.33	0.08	0.35	0.24	0.10	0.13	**0.22**	**0.22**
O61	0.06	0.16	0.22	0.29	0.38	0.42	0.37	0.02	0.05	0.10	0.20	**0.25**	**0.21**
O62	0.04	0.12	0.22	0.22	0.22	0.18	0.16	0.02	0.05	0.09	0.27	**0.17**	**0.14**
O63	0.09	0.11	0.28	0.36	0.16	0.24	0.21	0.03	0.04	0.04	0.36	**0.20**	**0.16**
O64	0.17	0.04	0.24	0.32	0.16	0.19	0.19	0.06	0.11	0.03	0.38	**0.18**	**0.16**
O65	0.25	0.32	0.22	0.31	0.26	0.12	0.11	0.11	0.13	0.11	0.47	**0.24**	**0.19**
O66	0.34	0.46	0.40	0.16	0.39	0.52	0.36	0.28	0.18	0.12	0.26	**0.32**	**0.27**
O67	0.32	0.38	0.39	0.26	0.45	0.22	0.19	0.17	0.16	0.29	0.41	**0.32**	**0.27**
O68	0.23	0.22	0.24	0.36	0.32	0.14	0.10	0.08	0.09	0.18	0.49	**0.25**	**0.21**
O69	0.09	0.26	0.31	0.40	0.18	0.27	0.27	0.04	0.01	0.06	0.50	**0.24**	**0.19**
O70	0.06	0.29	0.37	0.41	0.21	0.32	0.27	0.01	0.06	0.04	0.42	**0.26**	**0.19**
O71	0.09	0.27	0.41	0.45	0.31	0.41	0.34	0.11	0.11	0.21	0.49	**0.32**	**0.28**
O72	0.13	0.24	0.39	0.45	0.23	0.41	0.35	0.07	0.08	0.23	0.51	**0.30**	**0.27**
O73	0.08	0.21	0.39	0.45	0.25	0.33	0.26	0.03	0.03	0.28	0.47	**0.29**	**0.24**
O74	0.15	0.37	0.40	0.33	0.34	0.10	0.05	0.08	0.01	0.34	0.39	**0.28**	**0.20**
O75	0.29	0.33	0.31	0.09	0.41	0.19	0.14	0.15	0.11	0.11	0.23	**0.23**	**0.18**
O76	0.31	0.40	0.45	0.34	0.36	0.43	0.30	0.20	0.16	0.04	0.22	**0.33**	**0.24**

	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	Combined Annual	Combined Summer
O77	0.06	0.13	0.16	0.42	0.36	0.48	0.34	0.05	0.08	0.35	0.34	**0.29**	**0.29**
O78	0.20	0.08	0.14	0.39	0.28	0.36	0.22	0.13	0.04	0.28	0.17	**0.25**	**0.22**
O79	0.20	0.09	0.09	0.22	0.45	0.53	0.38	0.13	0.06	0.09	0.06	**0.24**	**0.22**
O80	0.04	0.27	0.29	0.07	0.38	0.45	0.33	0.05	0.06	0.11	0.22	**0.22**	**0.20**
O81	0.06	0.29	0.33	0.10	0.09	0.25	0.19	0.09	0.03	0.11	0.23	**0.16**	**0.13**
O82	0.16	0.29	0.32	0.34	0.11	0.15	0.11	0.06	0.06	0.06	0.30	**0.21**	**0.13**
O83	0.12	0.26	0.22	0.19	0.19	0.36	0.30	0.15	0.06	0.03	0.18	**0.19**	**0.17**
O84	0.06	0.09	0.10	0.20	0.29	0.22	0.24	0.12	0.14	0.02	0.16	**0.16**	**0.16**

A2 VR Result for Proposed Scheme

Table A- 3 VR of Perimeter Test Points for Proposed Scheme

	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	Combined Annual	Combined Summer
Freq. Annual	6.4%	8.2%	10.2%	17.2%	14.7%	8.6%			6.5%	5.5%		**77.3%**	
Freq. Summer				7.3%	10.3%	8.9%	8.9%	9.7%	14.0%	13.0%	8.9%		**81.0%**
P1	0.06	0.22	0.31	0.25	0.48	0.68	0.46	0.16	0.12	0.09	0.29	**0.31**	**0.29**
P2	0.05	0.24	0.33	0.24	0.47	0.67	0.51	0.13	0.06	0.09	0.10	**0.30**	**0.26**
P3	0.01	0.27	0.34	0.22	0.48	0.64	0.50	0.14	0.07	0.08	0.09	**0.30**	**0.26**
P4	0.24	0.28	0.30	0.19	0.45	0.58	0.48	0.50	0.29	0.06	0.07	**0.31**	**0.32**
P5	0.37	0.28	0.23	0.18	0.36	0.52	0.45	0.48	0.30	0.05	0.11	**0.29**	**0.30**
P6	0.32	0.21	0.15	0.15	0.25	0.44	0.37	0.30	0.17	0.06	0.17	**0.22**	**0.23**
P7	0.32	0.09	0.10	0.15	0.32	0.47	0.40	0.33	0.25	0.06	0.21	**0.22**	**0.27**
P8	0.31	0.06	0.05	0.17	0.35	0.48	0.41	0.34	0.30	0.06	0.13	**0.23**	**0.27**
P9	0.34	0.10	0.09	0.23	0.34	0.47	0.40	0.34	0.27	0.06	0.06	**0.25**	**0.26**
P10	0.41	0.15	0.07	0.28	0.37	0.55	0.43	0.50	0.24	0.08	0.07	**0.28**	**0.30**
P11	0.24	0.17	0.06	0.31	0.41	0.62	0.49	0.55	0.31	0.06	0.05	**0.29**	**0.34**
P12	0.33	0.28	0.09	0.12	0.38	0.57	0.44	0.55	0.31	0.02	0.06	**0.26**	**0.30**
P13	0.35	0.30	0.06	0.16	0.26	0.40	0.31	0.50	0.28	0.03	0.07	**0.22**	**0.24**
P14	0.32	0.30	0.08	0.23	0.17	0.26	0.19	0.47	0.25	0.02	0.06	**0.20**	**0.20**
P15	0.30	0.32	0.15	0.29	0.15	0.16	0.12	0.46	0.24	0.01	0.05	**0.21**	**0.18**
P16	0.29	0.38	0.29	0.34	0.20	0.13	0.17	0.46	0.26	0.01	0.04	**0.25**	**0.19**
P17	0.29	0.36	0.38	0.27	0.24	0.08	0.22	0.41	0.28	0.06	0.55	**0.26**	**0.26**
P18	0.05	0.14	0.40	0.51	0.40	0.48	0.33	0.29	0.07	0.14	0.60	**0.33**	**0.32**
P19	0.08	0.13	0.25	0.45	0.53	0.68	0.53	0.49	0.03	0.19	0.45	**0.35**	**0.38**
P20	0.10	0.10	0.13	0.30	0.39	0.47	0.37	0.36	0.02	0.19	0.40	**0.24**	**0.29**
P21	0.02	0.03	0.11	0.09	0.04	0.54	0.42	0.40	0.03	0.19	0.27	**0.12**	**0.23**
P22	0.02	0.07	0.05	0.11	0.13	0.40	0.30	0.20	0.02	0.14	0.23	**0.12**	**0.18**
P23	0.22	0.26	0.11	0.05	0.22	0.41	0.30	0.14	0.10	0.14	0.10	**0.18**	**0.18**
P24	0.37	0.43	0.39	0.30	0.05	0.57	0.44	0.24	0.17	0.12	0.33	**0.29**	**0.26**
P25	0.35	0.39	0.35	0.36	0.14	0.36	0.21	0.09	0.17	0.21	0.32	**0.29**	**0.22**
P26	0.29	0.30	0.30	0.40	0.08	0.06	0.10	0.05	0.13	0.02	0.37	**0.22**	**0.14**
P27	0.21	0.22	0.28	0.38	0.16	0.08	0.08	0.06	0.11	0.03	0.38	**0.21**	**0.14**
P28	0.15	0.21	0.32	0.33	0.33	0.03	0.06	0.28	0.12	0.04	0.37	**0.23**	**0.18**
P29	0.10	0.22	0.34	0.29	0.43	0.07	0.15	0.22	0.13	0.07	0.33	**0.25**	**0.20**

Table A- 4 VR of Overall Test Points for Baseline Scheme

	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	Combined Annual	Combined Summer
Freq. Annual	6.4%	8.2%	10.2%	17.2%	14.7%	8.6%			6.5%	5.5%		**77.3%**	
Freq. Summer				7.3%	10.3%	8.9%	8.9%	9.7%	14.0%	13.0%	8.9%		**81.0%**
O1	0.12	0.22	0.29	0.07	0.36	0.50	0.42	0.11	0.04	0.24	0.28	**0.23**	**0.24**
O2	0.09	0.20	0.23	0.06	0.27	0.46	0.43	0.16	0.05	0.23	0.37	**0.19**	**0.24**
O3	0.08	0.16	0.13	0.07	0.15	0.23	0.22	0.16	0.11	0.17	0.38	**0.13**	**0.18**
O4	0.16	0.27	0.35	0.19	0.45	0.50	0.29	0.03	0.15	0.16	0.36	**0.30**	**0.26**
O5	0.14	0.27	0.29	0.21	0.48	0.50	0.31	0.03	0.12	0.07	0.48	**0.29**	**0.26**
O6	0.14	0.25	0.25	0.27	0.50	0.51	0.32	0.05	0.09	0.07	0.56	**0.30**	**0.27**
O7	0.12	0.20	0.27	0.32	0.51	0.49	0.25	0.09	0.13	0.09	0.38	**0.31**	**0.27**
O8	0.09	0.15	0.25	0.30	0.49	0.59	0.35	0.11	0.16	0.09	0.18	**0.30**	**0.27**
O9	0.02	0.10	0.17	0.17	0.24	0.42	0.33	0.07	0.09	0.06	0.42	**0.18**	**0.21**
O10	0.06	0.29	0.35	0.28	0.26	0.16	0.25	0.25	0.14	0.02	0.25	**0.23**	**0.19**
O11	0.30	0.38	0.36	0.28	0.12	0.34	0.22	0.43	0.14	0.04	0.11	**0.25**	**0.20**
O12	0.07	0.12	0.16	0.23	0.14	0.09	0.29	0.20	0.08	0.04	0.11	**0.14**	**0.14**
O13	0.25	0.22	0.21	0.14	0.07	0.22	0.31	0.24	0.26	0.09	0.14	**0.17**	**0.18**
O14	0.36	0.30	0.29	0.20	0.07	0.32	0.22	0.34	0.21	0.04	0.17	**0.21**	**0.19**
O15	0.31	0.34	0.26	0.09	0.10	0.34	0.29	0.28	0.23	0.06	0.27	**0.20**	**0.20**
O16	0.17	0.33	0.17	0.10	0.10	0.08	0.11	0.05	0.08	0.09	0.06	**0.13**	**0.08**
O17	0.33	0.32	0.25	0.11	0.11	0.15	0.10	0.29	0.38	0.16	0.17	**0.20**	**0.20**
O18	0.33	0.38	0.29	0.06	0.12	0.09	0.11	0.31	0.43	0.14	0.19	**0.20**	**0.20**
O19	0.32	0.36	0.26	0.09	0.09	0.24	0.34	0.28	0.40	0.10	0.10	**0.20**	**0.21**
O20	0.27	0.15	0.08	0.23	0.35	0.36	0.35	0.23	0.34	0.10	0.11	**0.24**	**0.26**
O21	0.20	0.09	0.04	0.22	0.35	0.28	0.36	0.14	0.26	0.09	0.22	**0.21**	**0.24**
O22	0.05	0.11	0.03	0.22	0.36	0.30	0.36	0.20	0.37	0.08	0.20	**0.21**	**0.26**
O23	0.08	0.09	0.05	0.21	0.37	0.28	0.35	0.28	0.50	0.08	0.18	**0.22**	**0.29**
O24	0.33	0.02	0.06	0.19	0.31	0.16	0.33	0.15	0.22	0.08	0.24	**0.18**	**0.21**
O25	0.35	0.02	0.04	0.11	0.20	0.33	0.26	0.21	0.19	0.09	0.09	**0.16**	**0.18**
O26	0.34	0.01	0.02	0.11	0.22	0.36	0.30	0.31	0.21	0.10	0.14	**0.16**	**0.22**
O27	0.34	0.03	0.08	0.12	0.25	0.36	0.30	0.29	0.26	0.09	0.03	**0.18**	**0.21**
O28	0.15	0.03	0.05	0.04	0.04	0.06	0.14	0.18	0.28	0.02	0.16	**0.07**	**0.12**
O29	0.17	0.09	0.08	0.09	0.06	0.09	0.14	0.10	0.27	0.02	0.17	**0.10**	**0.12**
O30	0.11	0.21	0.16	0.18	0.11	0.11	0.11	0.10	0.18	0.06	0.16	**0.15**	**0.13**
O31	0.08	0.07	0.06	0.05	0.03	0.08	0.12	0.08	0.11	0.05	0.15	**0.06**	**0.08**
O32	0.07	0.33	0.28	0.25	0.07	0.16	0.13	0.16	0.13	0.09	0.12	**0.18**	**0.14**
O33	0.21	0.31	0.33	0.22	0.19	0.17	0.16	0.15	0.20	0.08	0.09	**0.22**	**0.16**
O34	0.16	0.19	0.24	0.10	0.10	0.08	0.06	0.17	0.13	0.08	0.15	**0.13**	**0.11**
O35	0.11	0.16	0.23	0.04	0.03	0.06	0.15	0.14	0.16	0.05	0.08	**0.10**	**0.09**
O36	0.08	0.17	0.24	0.03	0.09	0.17	0.17	0.17	0.06	0.05	0.06	**0.11**	**0.10**

	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	Combined Annual	Combined Summer
O37	0.07	0.12	0.25	0.11	0.15	0.26	0.18	0.28	0.18	0.04	0.06	**0.15**	**0.16**
O38	0.37	0.12	0.25	0.23	0.24	0.26	0.19	0.20	0.27	0.07	0.06	**0.23**	**0.19**
O39	0.40	0.20	0.27	0.27	0.27	0.21	0.18	0.12	0.20	0.08	0.06	**0.25**	**0.17**
O40	0.42	0.22	0.33	0.29	0.23	0.13	0.08	0.06	0.15	0.07	0.03	**0.24**	**0.13**
O41	0.27	0.18	0.30	0.24	0.07	0.09	0.05	0.13	0.23	0.04	0.55	**0.18**	**0.17**
O42	0.09	0.11	0.07	0.07	0.07	0.20	0.12	0.22	0.18	0.16	0.40	**0.11**	**0.18**
O43	0.15	0.14	0.28	0.16	0.07	0.19	0.10	0.29	0.22	0.03	0.31	**0.16**	**0.17**
O44	0.18	0.16	0.31	0.21	0.15	0.22	0.13	0.27	0.28	0.06	0.06	**0.20**	**0.17**
O45	0.12	0.11	0.28	0.08	0.09	0.20	0.16	0.17	0.08	0.06	0.15	**0.13**	**0.12**
O46	0.15	0.09	0.21	0.07	0.05	0.09	0.16	0.13	0.12	0.07	0.19	**0.10**	**0.11**
O47	0.05	0.05	0.06	0.06	0.11	0.13	0.11	0.09	0.14	0.11	0.30	**0.08**	**0.13**
O48	0.09	0.04	0.06	0.03	0.04	0.13	0.10	0.10	0.12	0.10	0.32	**0.07**	**0.12**
O49	0.11	0.09	0.09	0.08	0.15	0.22	0.15	0.20	0.27	0.19	0.15	**0.14**	**0.18**
O50	0.10	0.10	0.03	0.06	0.11	0.13	0.06	0.20	0.26	0.35	0.08	**0.12**	**0.18**
O51	0.12	0.09	0.05	0.07	0.29	0.35	0.19	0.36	0.44	0.31	0.14	**0.19**	**0.29**
O52	0.07	0.04	0.03	0.05	0.22	0.34	0.17	0.32	0.40	0.16	0.15	**0.15**	**0.24**
O53	0.39	0.20	0.31	0.25	0.20	0.06	0.07	0.04	0.08	0.03	0.22	**0.20**	**0.11**
O54	0.28	0.14	0.03	0.13	0.10	0.21	0.10	0.20	0.26	0.07	0.11	**0.14**	**0.15**
O55	0.22	0.18	0.03	0.07	0.08	0.36	0.21	0.43	0.51	0.15	0.17	**0.16**	**0.26**
O56	0.36	0.17	0.11	0.11	0.17	0.47	0.27	0.51	0.47	0.13	0.05	**0.22**	**0.28**
O57	0.35	0.21	0.26	0.22	0.16	0.43	0.21	0.48	0.47	0.15	0.20	**0.26**	**0.30**
O58	0.11	0.26	0.31	0.28	0.23	0.43	0.28	0.38	0.10	0.14	0.11	**0.25**	**0.23**
O59	0.13	0.25	0.20	0.16	0.12	0.22	0.19	0.11	0.05	0.13	0.14	**0.16**	**0.13**
O60	0.34	0.17	0.05	0.12	0.38	0.33	0.08	0.36	0.25	0.11	0.14	**0.22**	**0.22**
O61	0.08	0.15	0.22	0.26	0.37	0.43	0.39	0.03	0.03	0.12	0.20	**0.24**	**0.21**
O62	0.07	0.11	0.21	0.23	0.22	0.17	0.16	0.05	0.05	0.08	0.29	**0.17**	**0.15**
O63	0.15	0.12	0.28	0.37	0.16	0.24	0.23	0.08	0.05	0.05	0.37	**0.21**	**0.17**
O64	0.24	0.17	0.20	0.31	0.17	0.18	0.20	0.10	0.10	0.04	0.37	**0.20**	**0.17**
O65	0.26	0.25	0.17	0.31	0.28	0.20	0.17	0.18	0.09	0.11	0.48	**0.23**	**0.21**
O66	0.32	0.40	0.37	0.19	0.26	0.61	0.48	0.45	0.14	0.18	0.27	**0.30**	**0.31**
O67	0.37	0.46	0.37	0.31	0.42	0.43	0.31	0.31	0.15	0.29	0.42	**0.36**	**0.32**
O68	0.34	0.23	0.22	0.36	0.35	0.28	0.19	0.17	0.13	0.18	0.51	**0.28**	**0.26**
O69	0.17	0.24	0.27	0.41	0.19	0.30	0.32	0.10	0.04	0.07	0.51	**0.24**	**0.22**
O70	0.07	0.27	0.34	0.42	0.22	0.33	0.31	0.06	0.06	0.04	0.42	**0.26**	**0.21**
O71	0.09	0.29	0.44	0.47	0.32	0.42	0.39	0.05	0.14	0.22	0.50	**0.34**	**0.29**
O72	0.14	0.25	0.41	0.47	0.25	0.44	0.39	0.08	0.10	0.23	0.52	**0.32**	**0.29**
O73	0.09	0.23	0.39	0.46	0.26	0.38	0.29	0.13	0.02	0.28	0.49	**0.30**	**0.27**
O74	0.24	0.37	0.37	0.33	0.31	0.21	0.11	0.20	0.05	0.34	0.39	**0.29**	**0.23**
O75	0.35	0.31	0.30	0.09	0.38	0.40	0.29	0.33	0.14	0.13	0.23	**0.26**	**0.24**
O76	0.35	0.42	0.43	0.31	0.32	0.61	0.48	0.42	0.16	0.02	0.22	**0.34**	**0.29**

	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	Combined Annual	Combined Summer
O77	0.06	0.09	0.24	0.41	0.36	0.49	0.33	0.16	0.10	0.35	0.34	**0.29**	**0.30**
O78	0.21	0.06	0.20	0.39	0.25	0.34	0.17	0.20	0.04	0.29	0.17	**0.25**	**0.22**
O79	0.21	0.10	0.10	0.28	0.43	0.52	0.38	0.02	0.06	0.07	0.06	**0.25**	**0.21**
O80	0.04	0.28	0.31	0.23	0.39	0.44	0.31	0.07	0.06	0.10	0.22	**0.26**	**0.21**
O81	0.06	0.29	0.33	0.24	0.13	0.26	0.22	0.04	0.02	0.09	0.22	**0.19**	**0.14**
O82	0.18	0.30	0.33	0.32	0.12	0.23	0.16	0.24	0.08	0.05	0.30	**0.22**	**0.17**
O83	0.12	0.26	0.23	0.12	0.11	0.26	0.24	0.14	0.07	0.09	0.18	**0.16**	**0.14**
O84	0.07	0.09	0.11	0.20	0.25	0.08	0.11	0.08	0.10	0.17	0.15	**0.15**	**0.14**

Appendix B

Directional VR Vector Plots

B1 Baseline Scheme

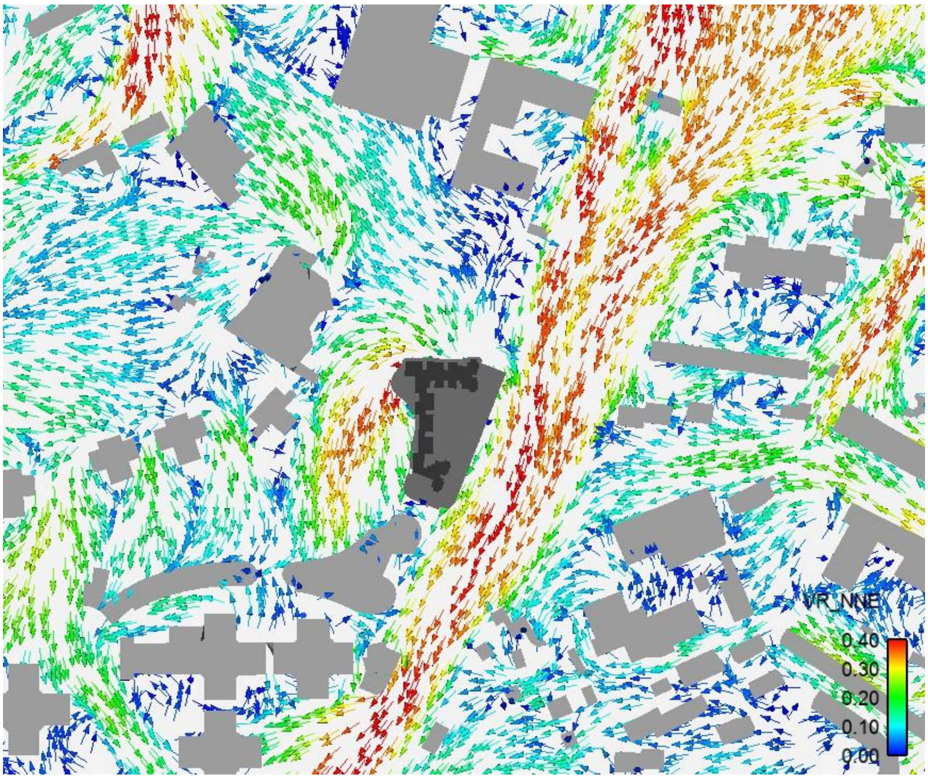


Figure B- 1 Vector Plot of VR under NNE Wind for Baseline Scheme

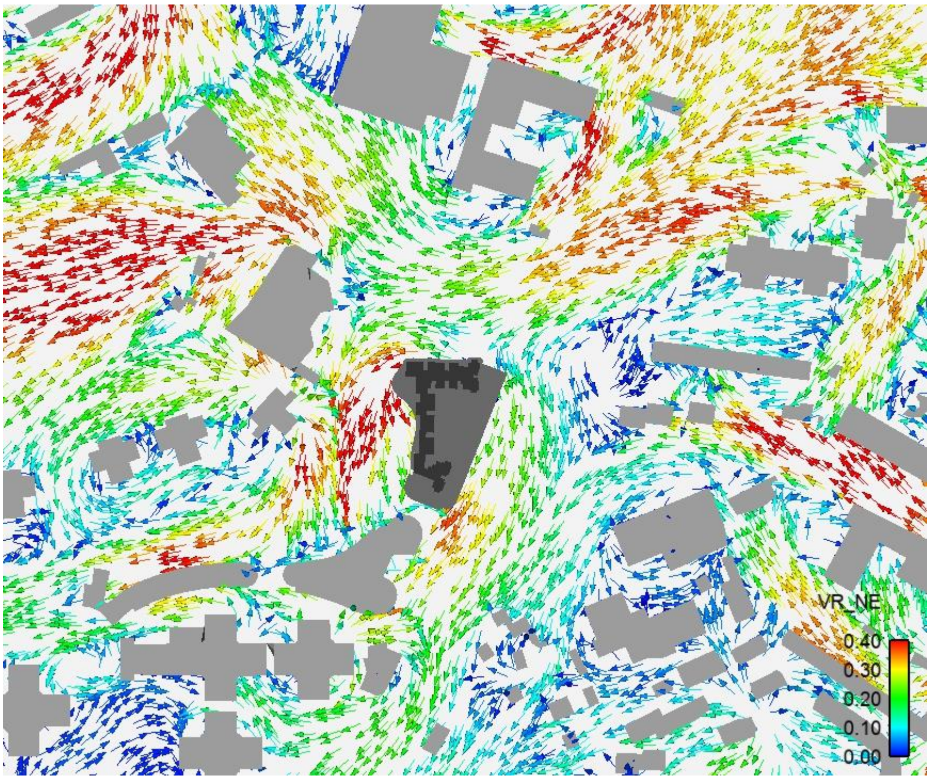


Figure B- 2 Vector Plot of VR under NE Wind for Baseline Scheme

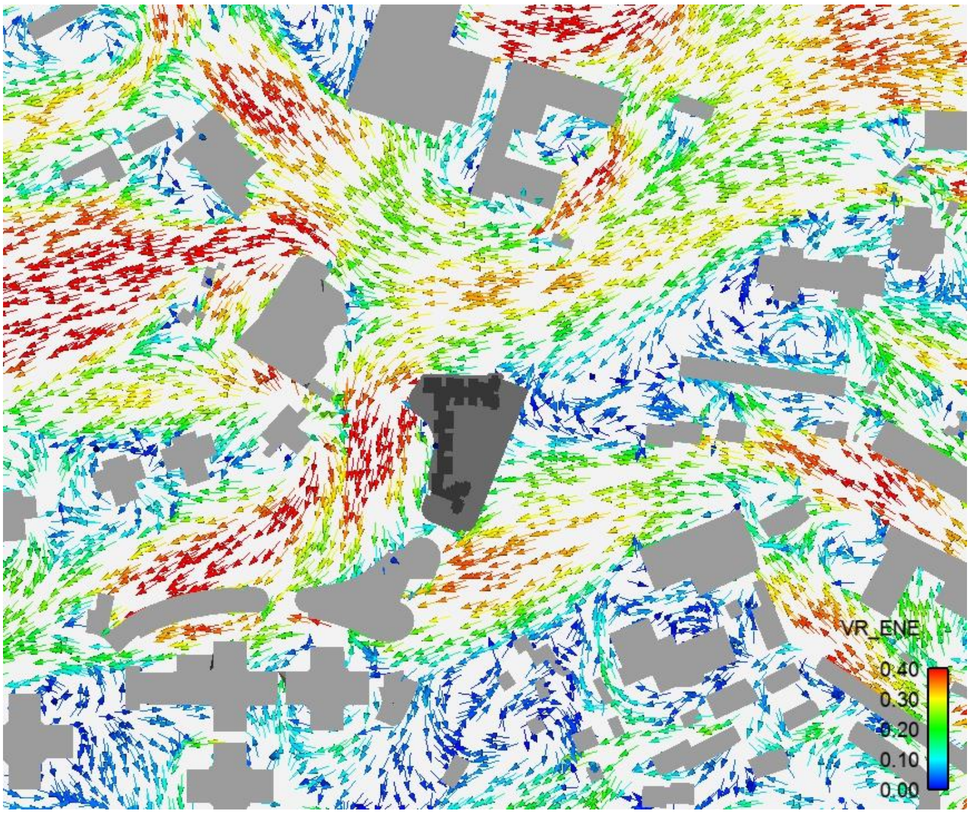


Figure B- 3 Vector Plot of VR under ENE Wind for Baseline Scheme

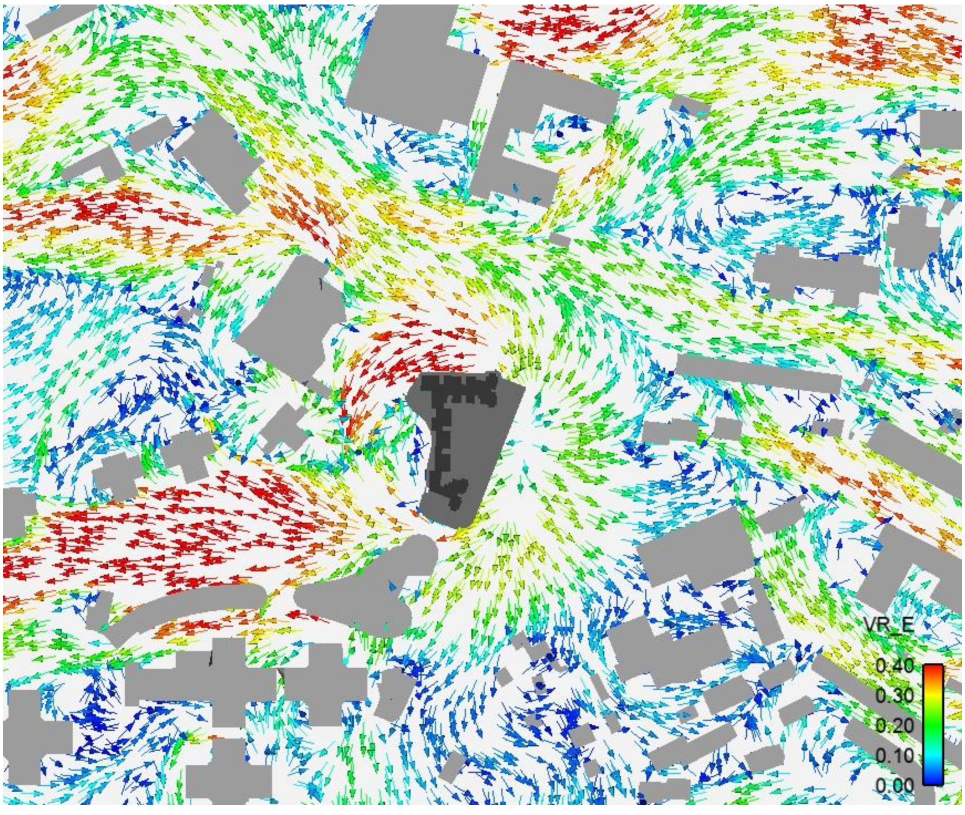


Figure B- 4 Vector Plot of VR under E Wind for Baseline Scheme

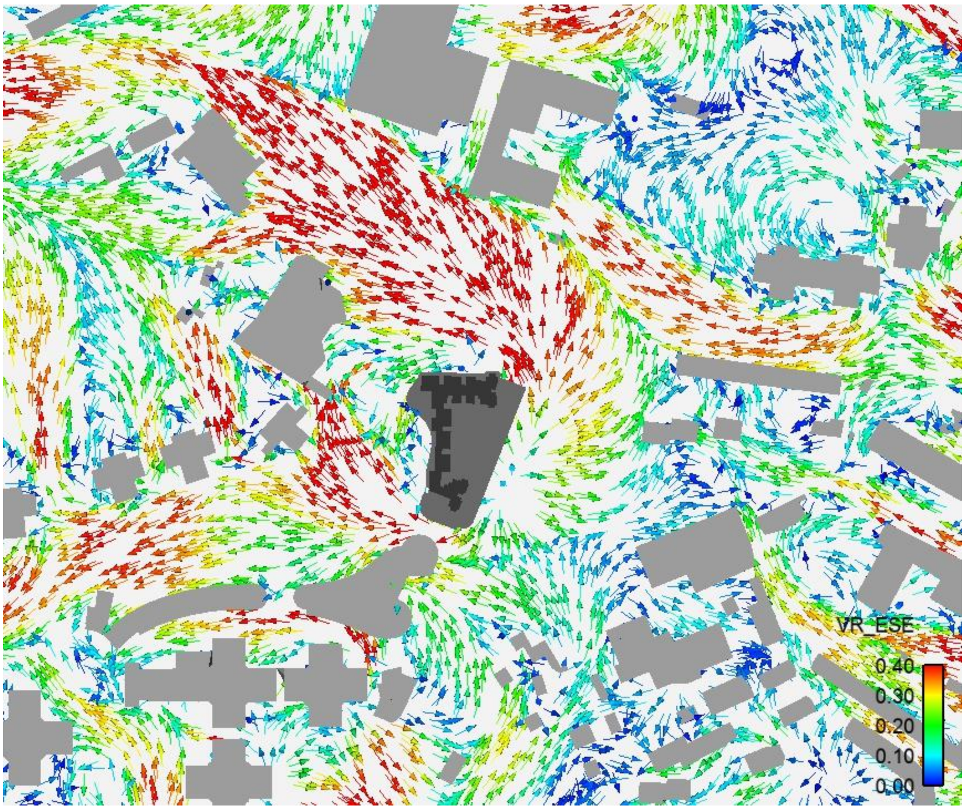


Figure B- 5 Vector Plot of VR under ESE Wind for Baseline Scheme

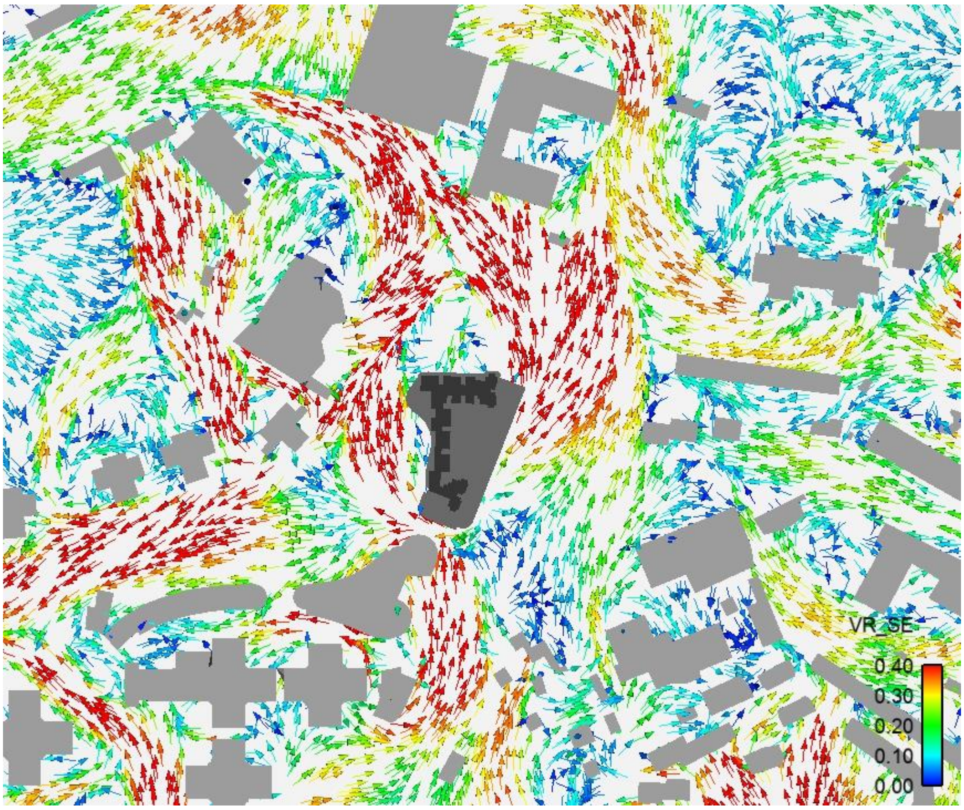


Figure B- 6 Vector Plot of VR under SE Wind for Baseline Scheme

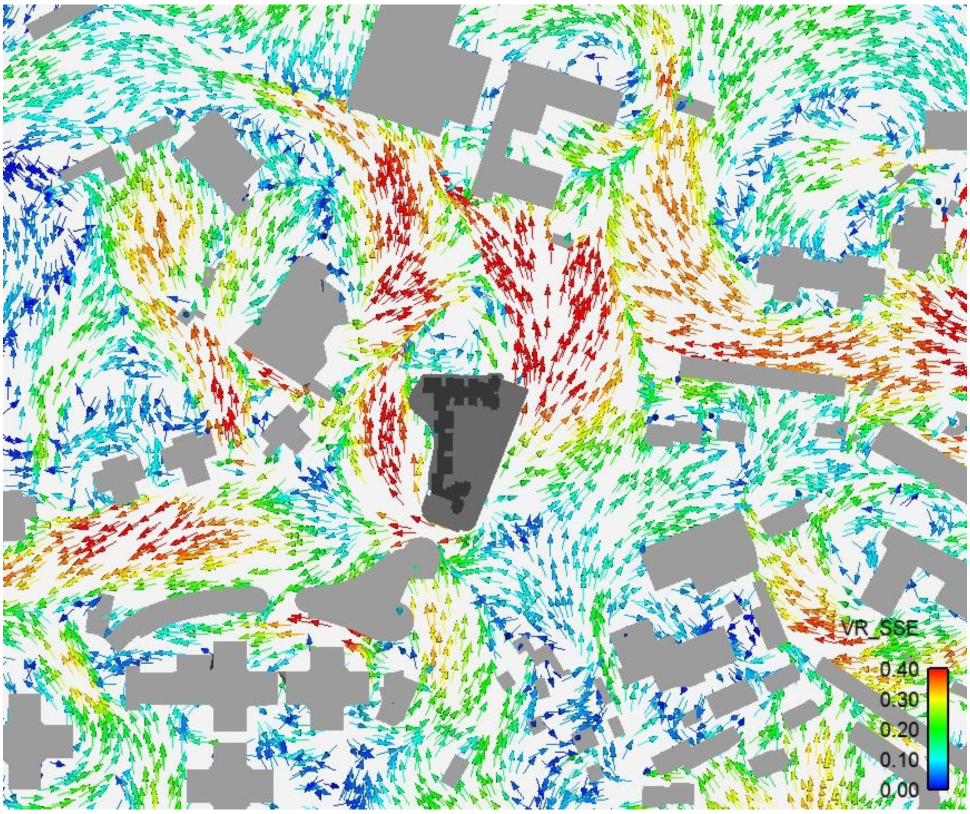


Figure B- 7 Vector Plot of VR under SSE Wind for Baseline Scheme

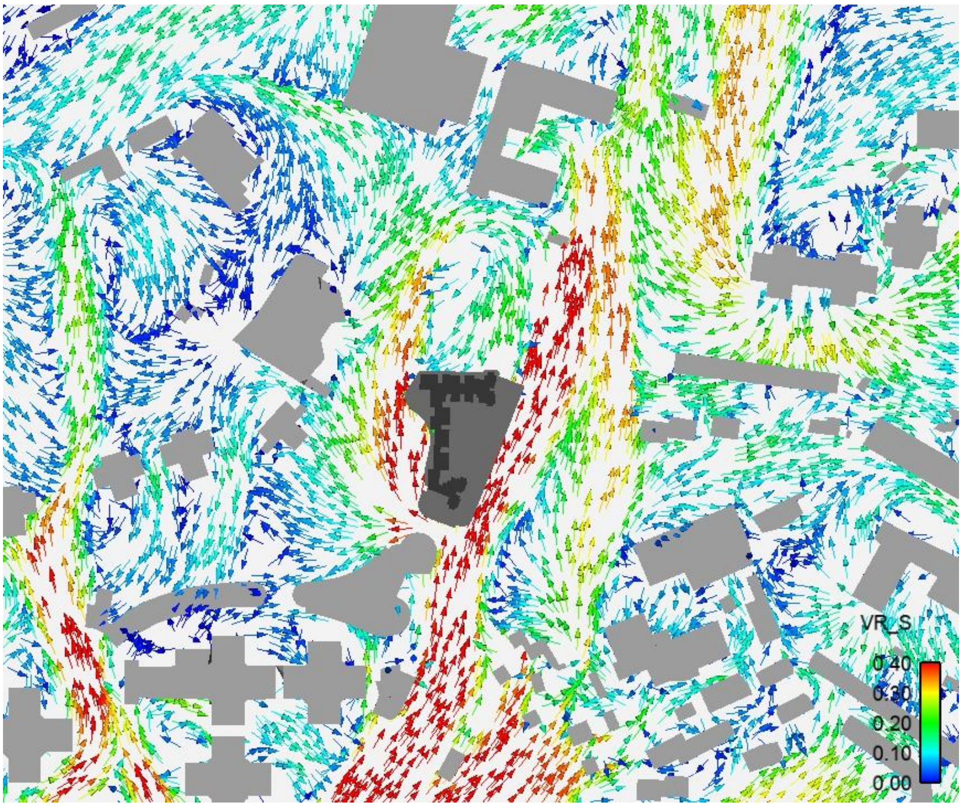


Figure B- 8 Vector Plot of VR under S Wind for Baseline Scheme

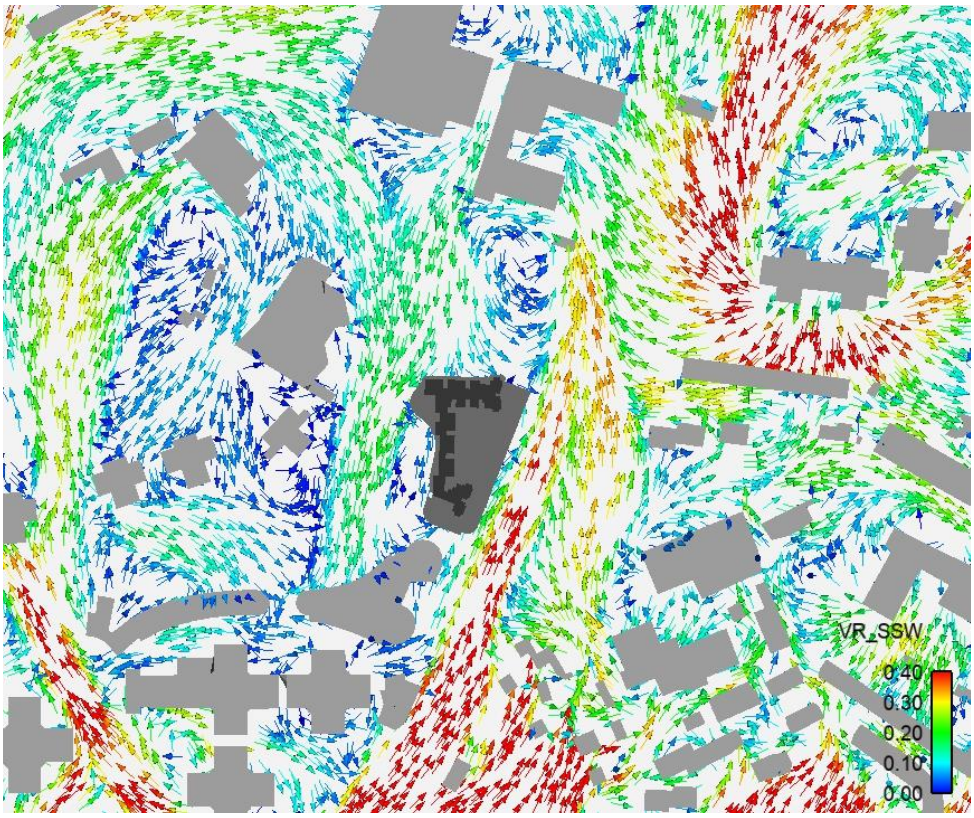


Figure B- 9 Vector Plot of VR under SSW Wind for Baseline Scheme

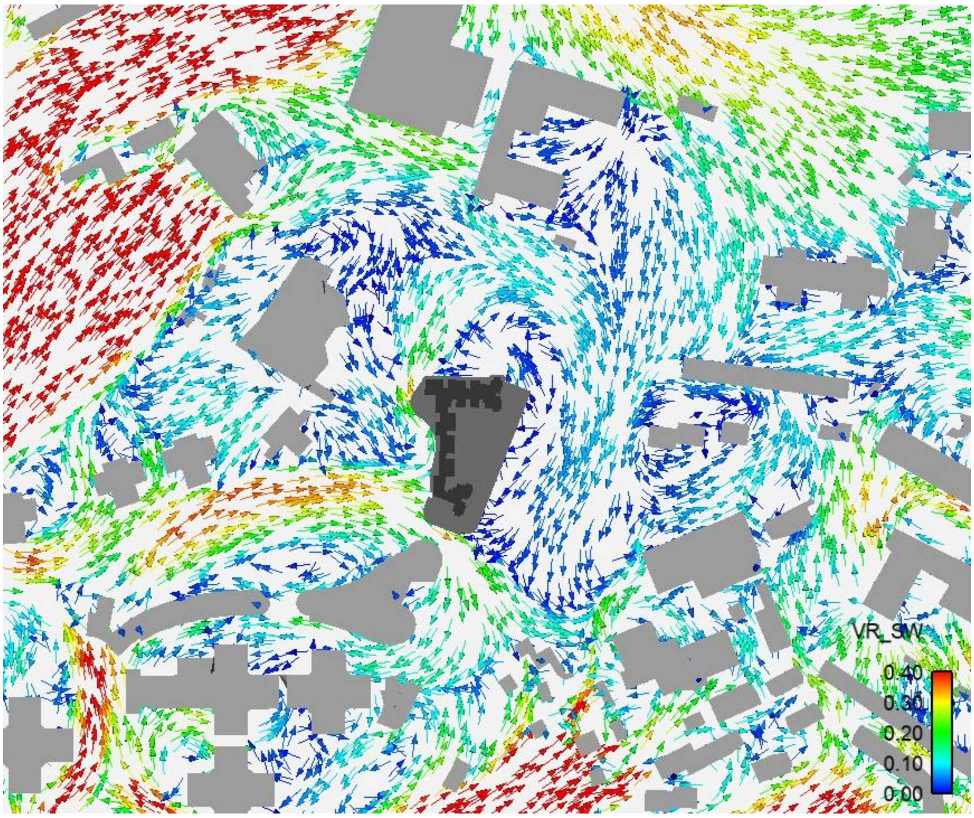


Figure B- 10 Vector Plot of VR under SW Wind for Baseline Scheme

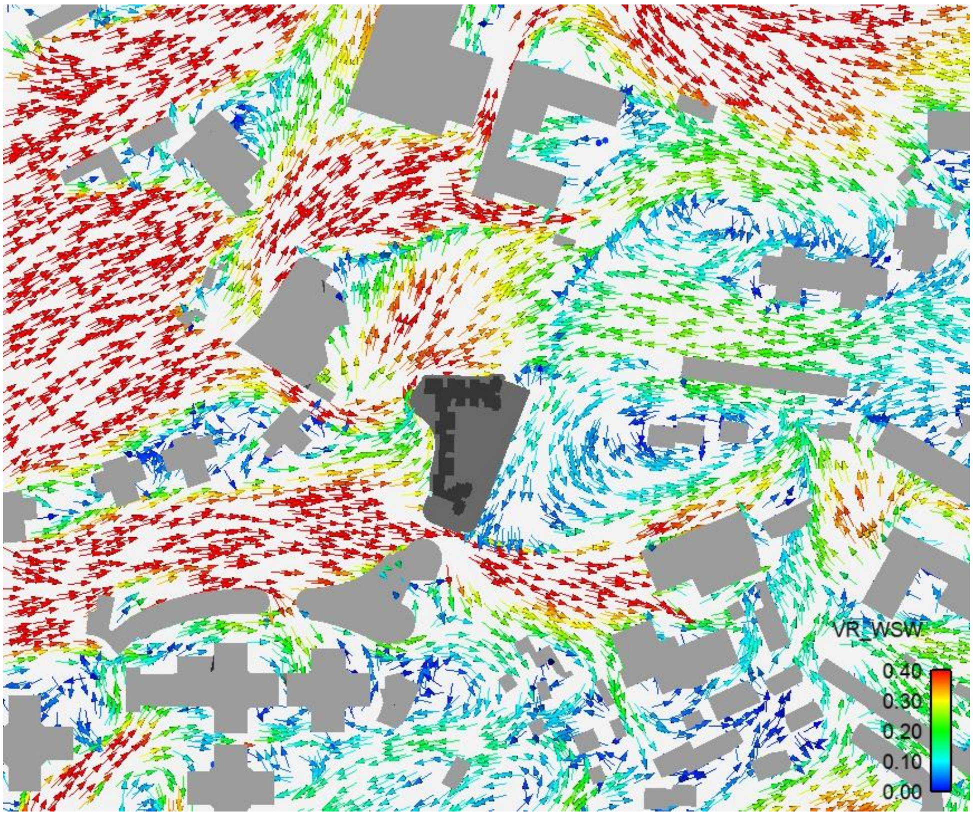


Figure B- 11 Vector Plot of VR under WSW Wind for Baseline Scheme

B2 Proposed Scheme

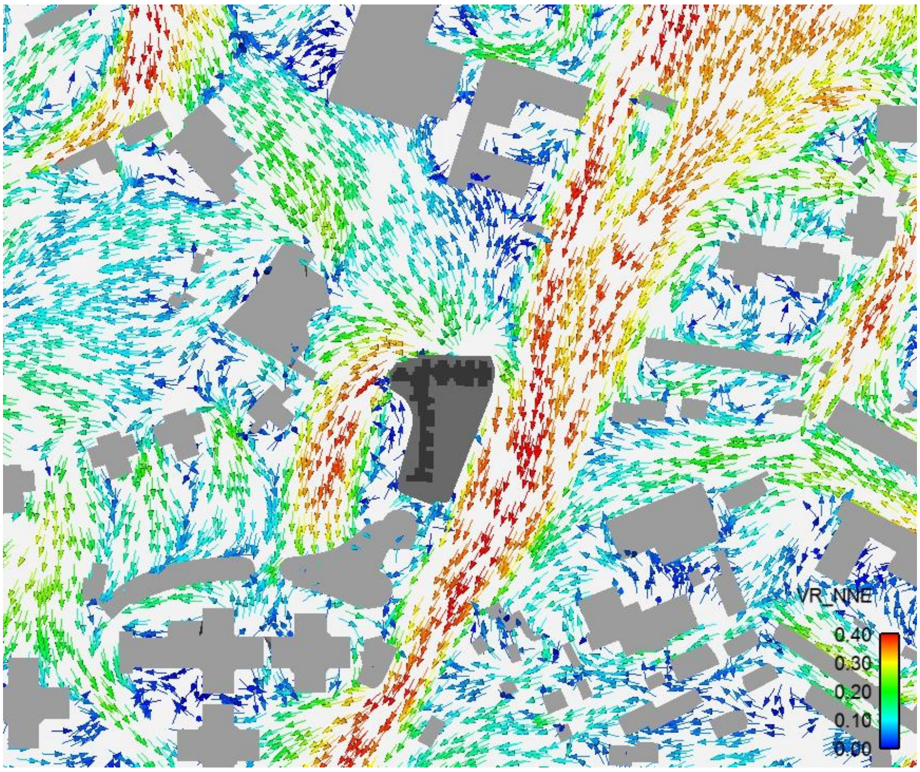


Figure B- 12 Vector Plot of VR under NNE Wind for Proposed Scheme

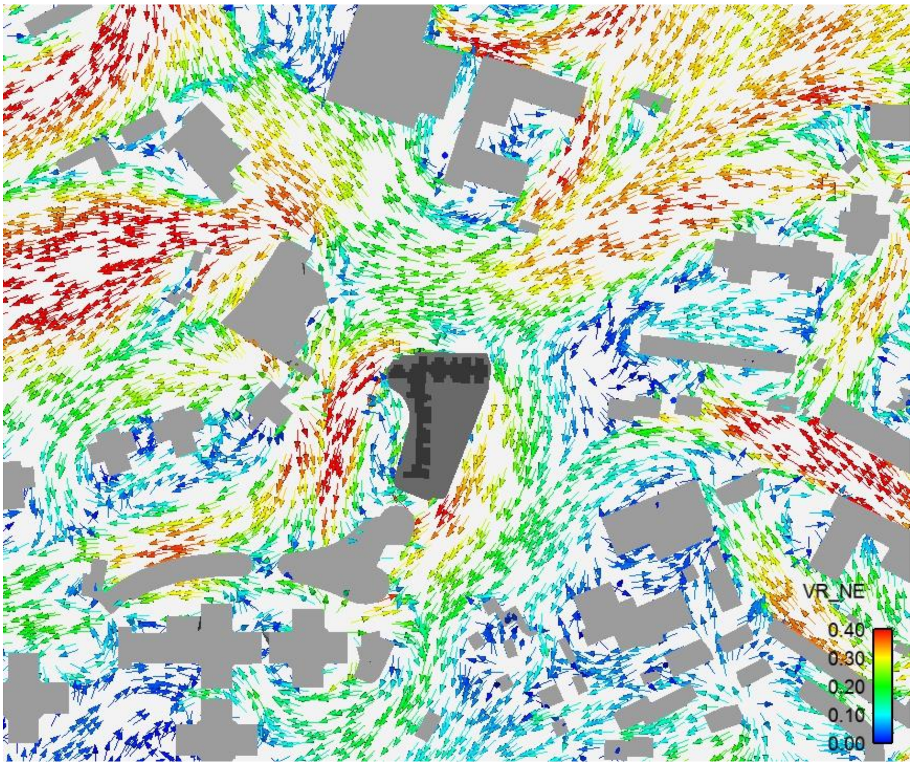


Figure B- 13 Vector Plot of VR under NE Wind for Proposed Scheme

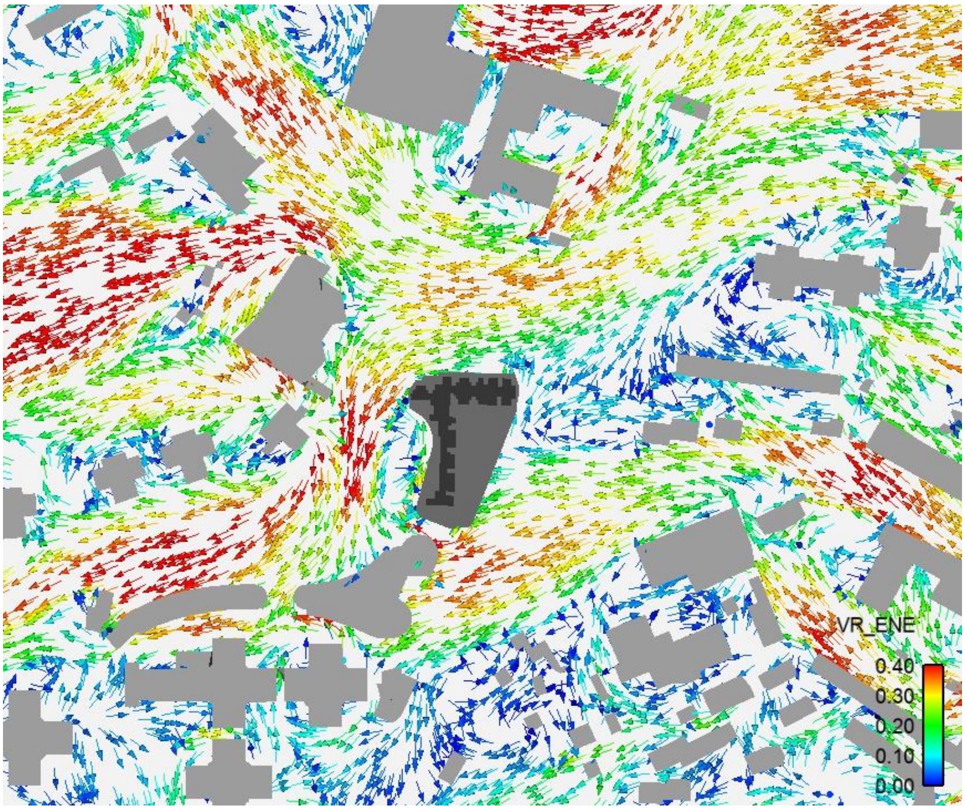


Figure B- 14 Vector Plot of VR under ENE Wind for Proposed Scheme

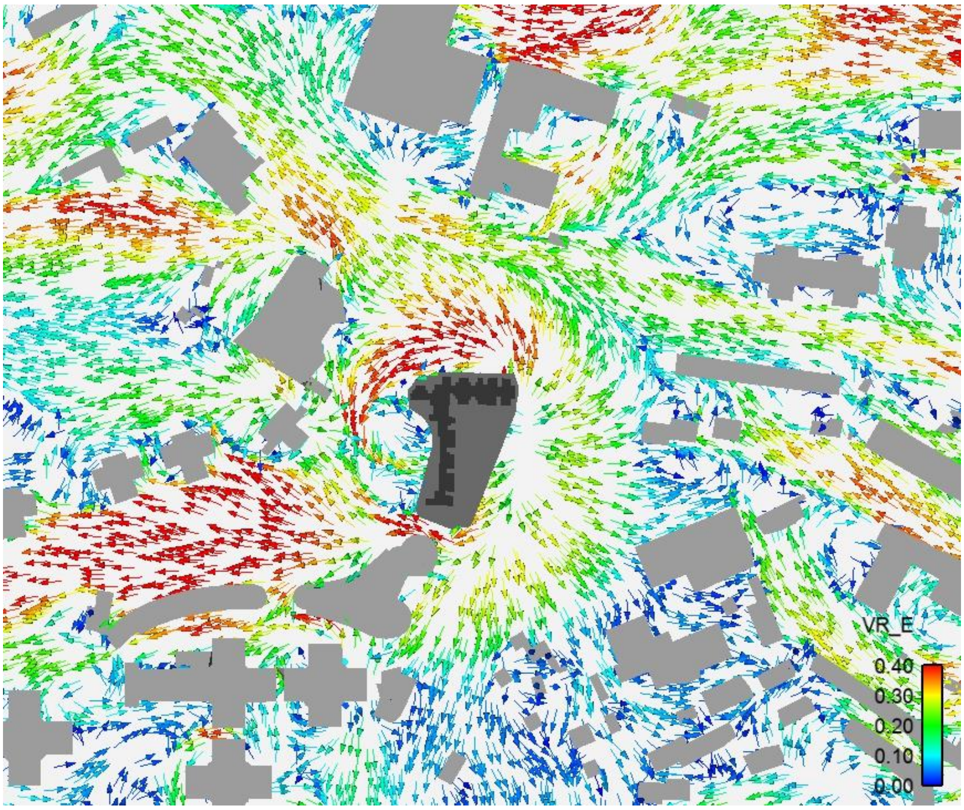


Figure B- 15 Vector Plot of VR under E Wind for Proposed Scheme

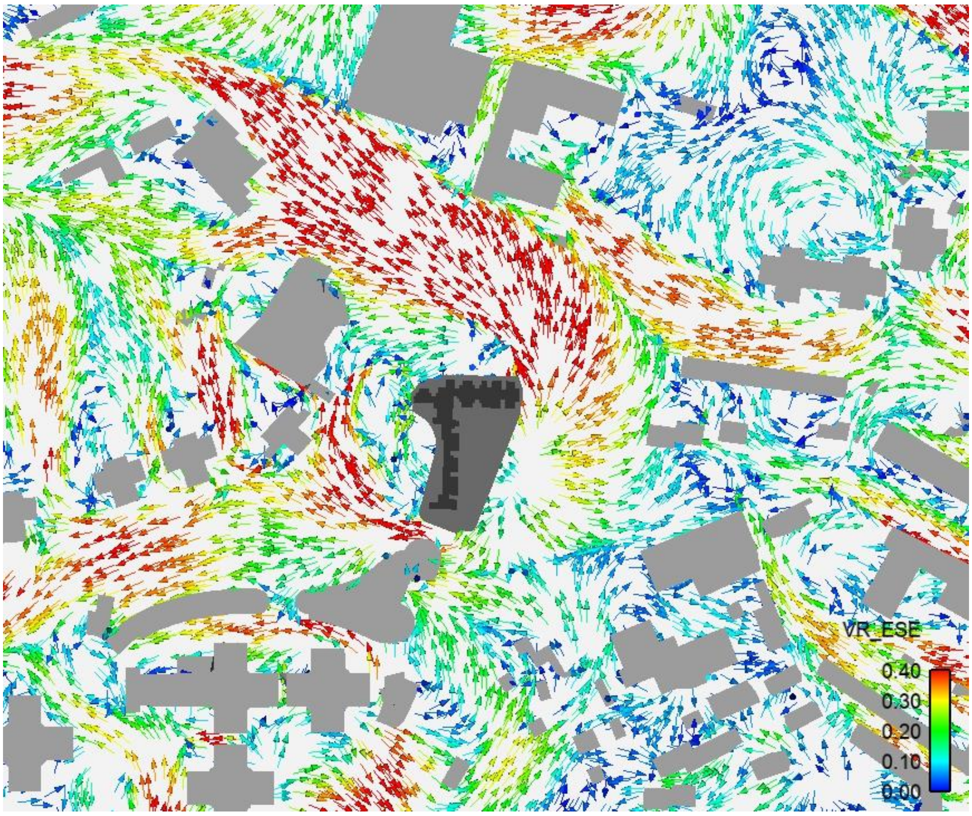


Figure B- 16 Vector Plot of VR under ESE Wind for Proposed Scheme

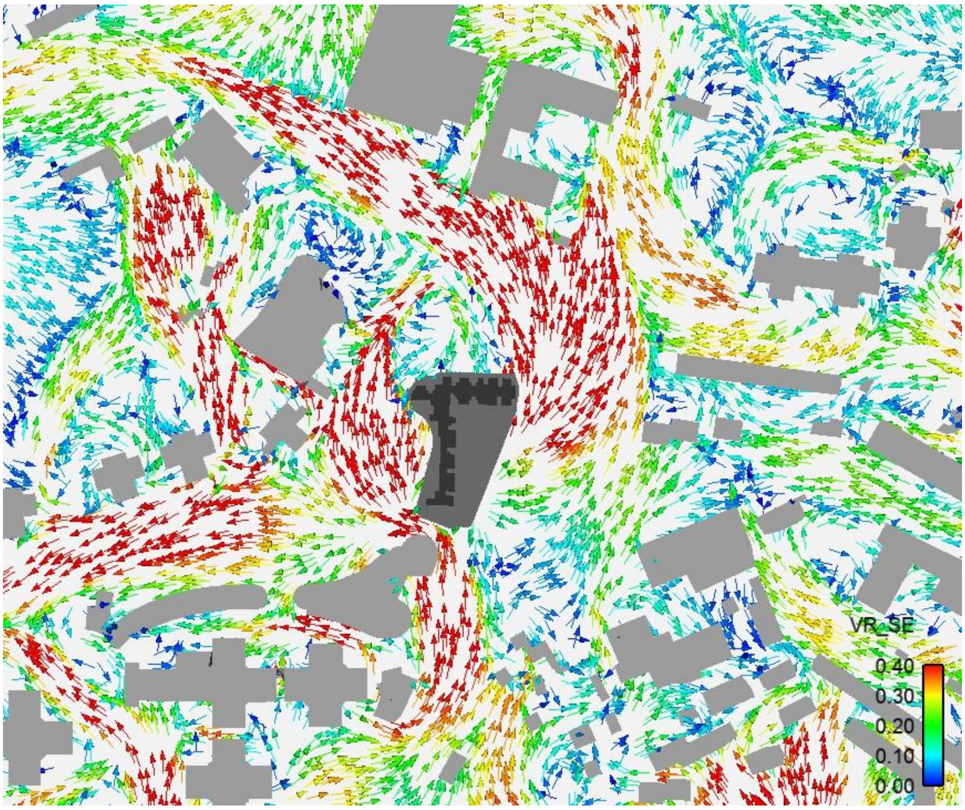


Figure B- 17 Vector Plot of VR under SE Wind for Proposed Scheme

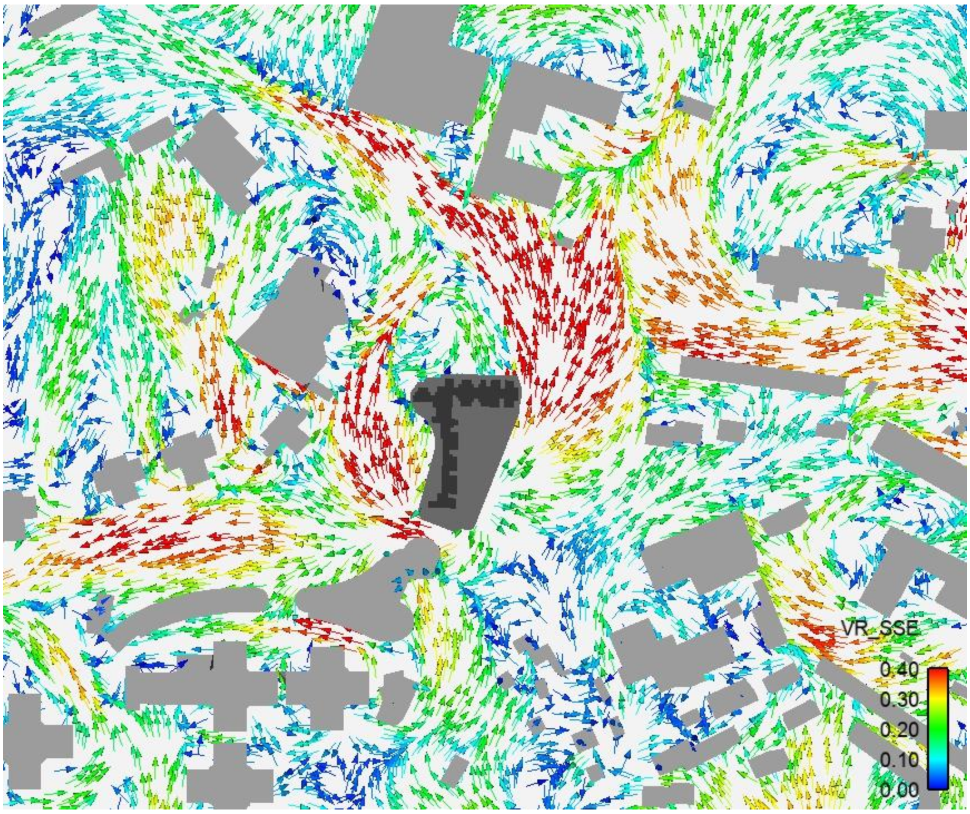


Figure B- 18 Vector Plot of VR under SSE Wind for Proposed Scheme

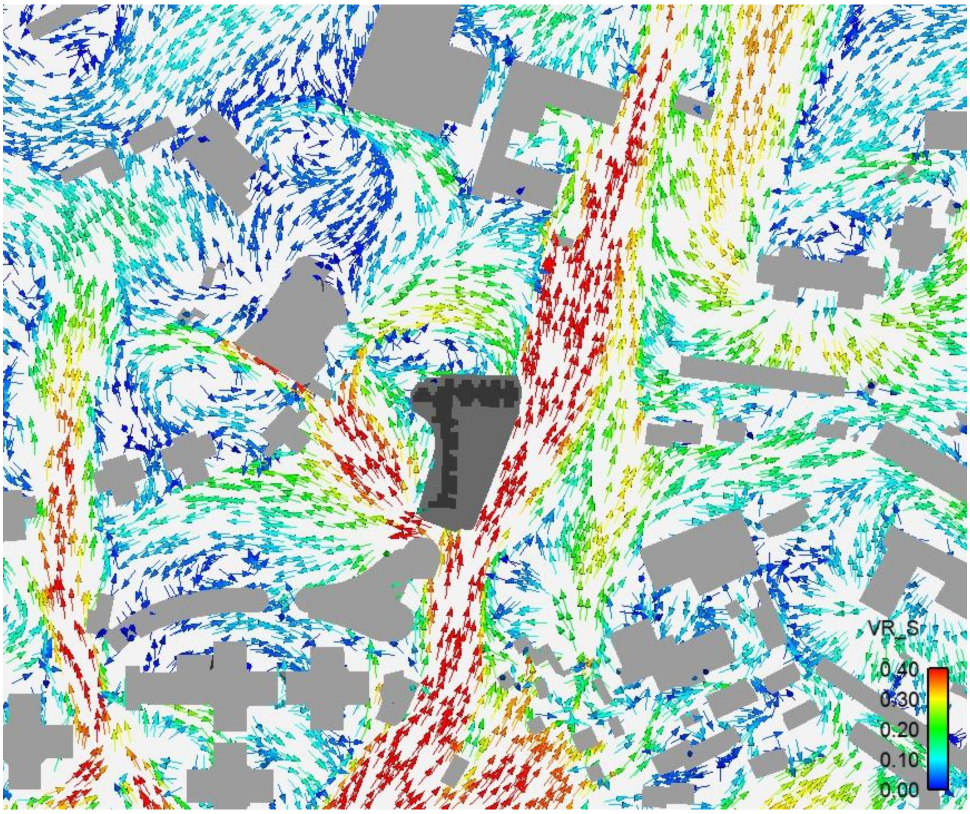


Figure B- 19 Vector Plot of VR under S Wind for Proposed Scheme

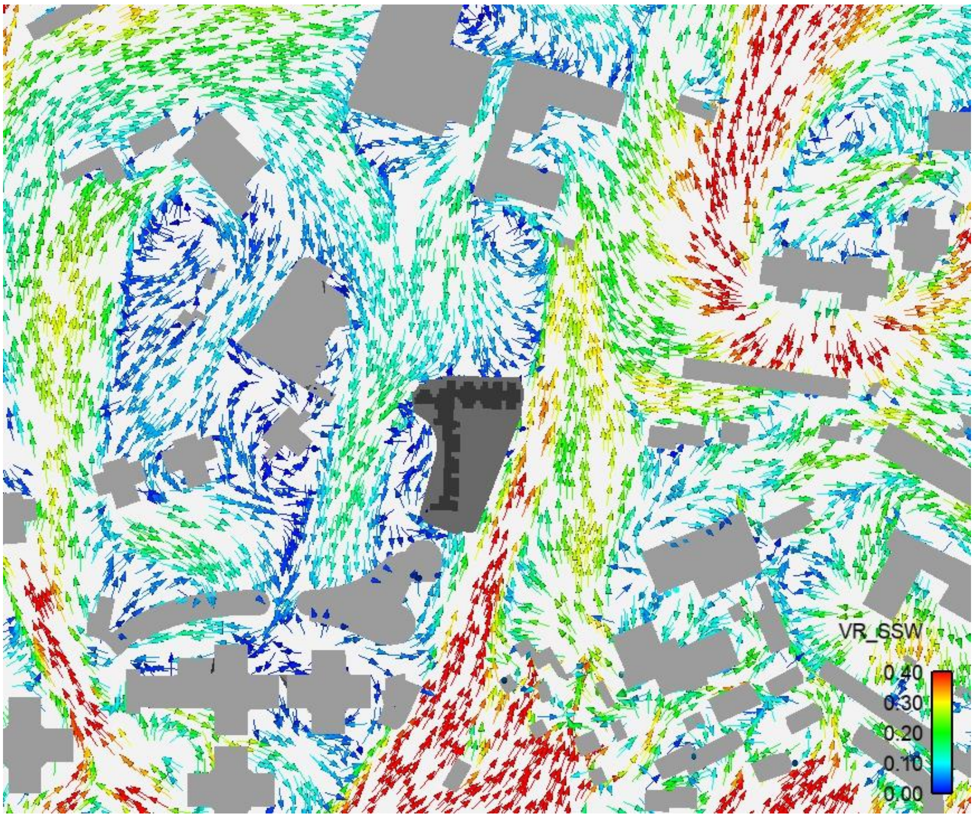


Figure B- 20 Vector Plot of VR under SSW Wind for Proposed Scheme

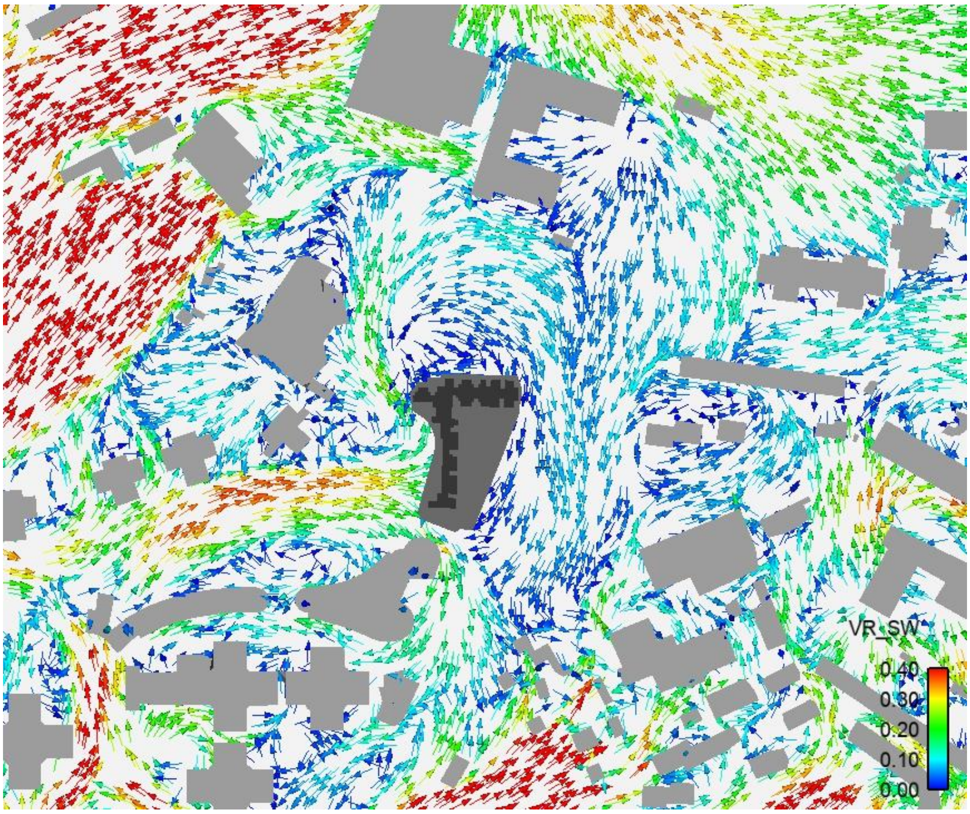


Figure B- 21 Vector Plot of VR under SW Wind for Proposed Scheme

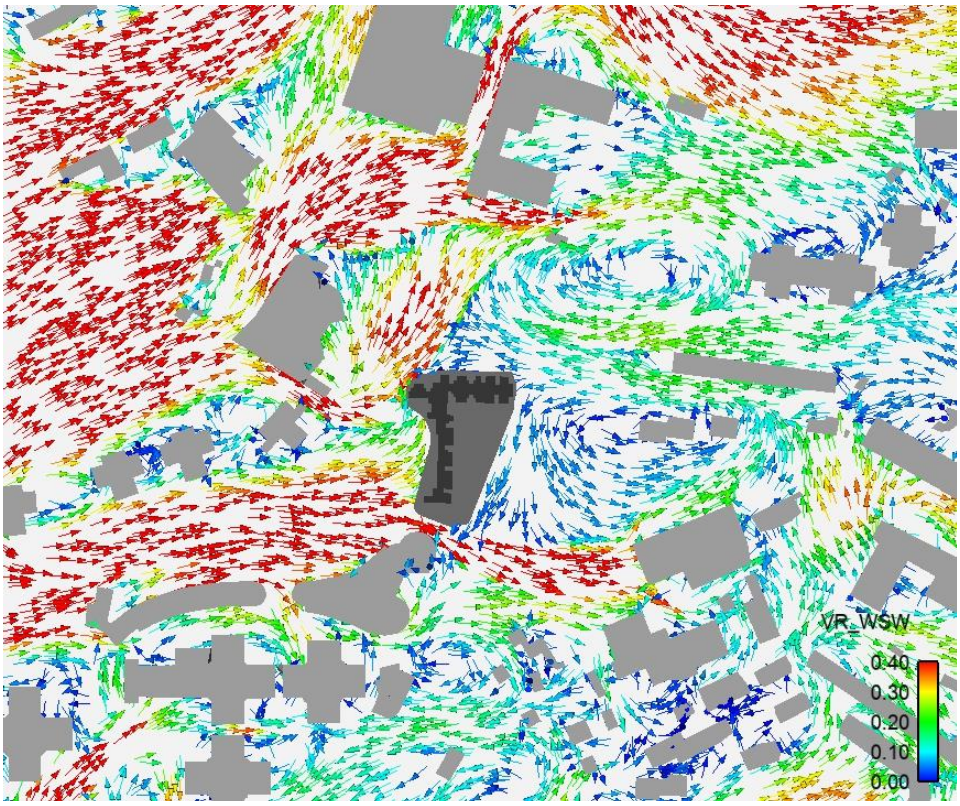


Figure B- 22 Vector Plot of VR under WSW Wind for Proposed Scheme