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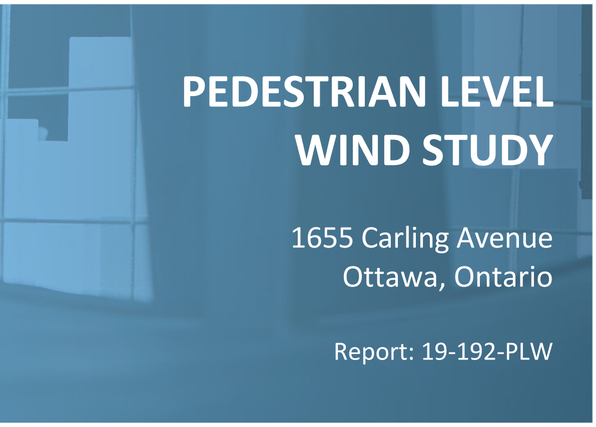
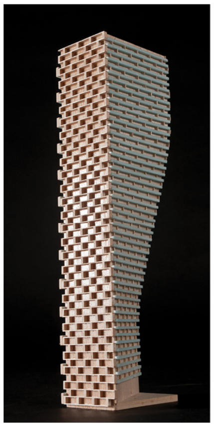
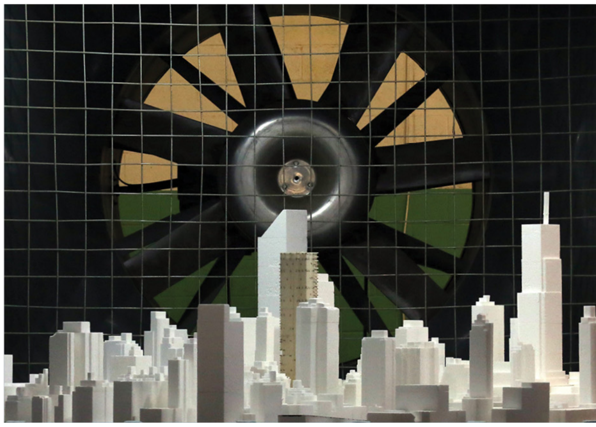


PEDESTRIAN LEVEL WIND STUDY

1655 Carling Avenue
Ottawa, Ontario

Report: 19-192-PLW





October 10, 2019

PREPARED FOR
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EXECUTIVE SUMMARY

This report describes a computer-based pedestrian level wind (PLW) study undertaken to satisfy the requirements for a site plan control application for a proposed development located at 1655 Carling Avenue in Ottawa, Ontario. Our mandate within this study, as outlined in Gradient Wind proposal #19-225P, dated August 9, 2019, is to investigate pedestrian wind comfort and safety within and surrounding the subject site, and to identify any areas where wind conditions may interfere with certain pedestrian activities so that mitigation measures may be considered, where necessary.

The study involves simulation of wind speeds for selected wind directions in a three-dimensional (3D) computer model using the computational fluid dynamics (CFD) technique, combined with meteorological data integration, to assess pedestrian comfort and safety within and surrounding the development site according to City of Ottawa wind comfort and safety criteria. The results and recommendations derived from these considerations are detailed in the main body of the report and summarized as follows:

1) Regarding wind comfort, conditions around the subject site at grade level are predicted to be moderately windy but nevertheless acceptable for all anticipated uses throughout the year.

2) Stronger wind conditions are predicted to occur within the amenity terrace on Level 7. To provide conditions suitable outright for sitting during the warmer months, mitigation will be required in the form of a tall perimeter wind screen, while a canopy is also suggested to protect the roof from downwash winds incident on the building itself. It would also be beneficial to shift the terrace south, towards the centre of the roof, thereby creating a buffer between the amenity area and the north perimeter of the roof. Additional simulations will be required to confirm the effectiveness of the preferred mitigation strategy, which will be performed during design development, as noted in Section 5.2.

3) Regarding wind safety, Figures 8A and 8B present extreme wind events over a small region of the amenity terrace on Level 7 considered to be dangerous for the more susceptible pedestrians. Figure 8A illustrates the area where gust wind speeds are predicted to exceed 90 km/h for more than 0.1% of the time (or 9 hours on an annual basis). The subject area is magnified for clarity in Figure 8B. The relevant area is the north side of the terrace, close to where the tower meets the

podium. The predicted peak value is 0.16% of the time or equivalently approximately 14 hours on an annual basis. The intensity of the wind is expected to be reduced to safe levels following adoption of the recommended mitigation outlined in Section 5.2.

4) Within the context of typical weather patterns, which exclude anomalous localized storm events such as tornadoes and downbursts, no areas surrounding the subject site at grade level were found to experience conditions that could be considered dangerous.

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1. INTRODUCTION

Gradient Wind Engineering Inc. (Gradient Wind) was retained by Independent Development Group to undertake a computer-based pedestrian level wind (PLW) study to satisfy the requirements for a site plan control application for a proposed development located at 1655 Carling Avenue in Ottawa, Ontario (hereinafter referred to as “subject site”). Our mandate within this study, as outlined in Gradient Wind proposal #19-225P, dated August 9, 2019, is to investigate pedestrian wind comfort and safety within and surrounding the subject site, and to identify any areas where wind conditions may interfere with certain pedestrian activities so that mitigation measures may be considered, where necessary.

Our work is based on industry standard computer simulations using the computational fluid dynamics (CFD) technique and data analysis procedures, City of Ottawa wind comfort and safety criteria, architectural drawings provided by Roderick Lahey Architect Inc. in late September 2019, surrounding street layouts and existing and approved future building massing information obtained from the City of Ottawa, as well as recent site imagery.

2. TERMS OF REFERENCE

The subject site is located at 1655 Carling Avenue in Ottawa and is situated on a parcel of land bordered by Tillbury Avenue to the north, Churchill Avenue to the east, Carling Avenue to the south, and Clyde Avenue to the west.

Axonometric Rendering Looking Southeast

The proposed development comprises a 22-storey tower with a 6-storey podium, rising approximately 70.5 meters (m) above grade to the top of the mechanical penthouse. The podium planform is rectangular with the long axis oriented along Carling Avenue. The main building access point is at the centre of the south elevation from Carling Avenue. Above the podium, the tower is sets back from the east and west sides of the building and from the north side slightly creating outdoor terraces. The rectangular tower planform shares the same orientation as the podium and is consistent until Level 22 where the floorplate sets back from the east elevation creating a terrace / green roof.

Regarding wind exposures, the near-field surroundings of the development (defined as an area falling within a 200-m radius of the site) are characterized by suburban low-rise residential developments along the north side of Carling Avenue and low-rise commercial developments on the south side. Farther away from the study site, the area composition is characterized by a mixture of parks and low-rise suburban buildings from the southeast clockwise to the southwest, and predominantly low-rise suburban exposure in all other directions. Bus stops are located 50 and 100 m to the east and west of the subject site, respectively. The Queensway is situated approximately 300 m to the south of the subject site, oriented southwest-northeast. An open exposure created by the Central Experimental Farm lies approximately 2 km to the southeast of the site, while the Ottawa River is approximately 2 km to the northwest.

Key areas under consideration for pedestrian wind comfort include surrounding sidewalks, walkways, building access points, nearby transit stops, the rooftop amenity terrace at Level 7, and the potential rooftop terrace / green roof at Level 22. Figure 1 illustrates the subject site and surrounding context, while Figures 2A-2D illustrate the computational model used to conduct the study.

3. OBJECTIVES

The principal objectives of this study are to (i) determine pedestrian level wind comfort and safety conditions at key areas within and surrounding the development site; (ii) identify areas where wind conditions may interfere with the intended uses of outdoor spaces; and (iii) recommend suitable mitigation measures, where required.

4. METHODOLOGY

The approach followed to quantify pedestrian wind conditions over the site is based on CFD simulations of wind speeds across the study site within a virtual environment, meteorological analysis of the Ottawa area wind climate, and synthesis of computational data with City of Ottawa wind comfort and safety criteria[1]. The following sections describe the analysis procedures, including a discussion of the noted pedestrian wind criteria.

4.1 Computer-Based Context Modelling

A computer-based PLW study was performed to determine the influence of the wind environment on pedestrian comfort over the proposed development site. Pedestrian comfort predictions, based on the mechanical effects of wind, were determined by combining measured wind speed data from CFD simulations with statistical weather data obtained from Ottawa's Macdonald-Cartier International Airport.

The general concept and approach to CFD modelling is to represent building and topographic details in the immediate vicinity of the study site on the surrounding model, and to create suitable atmospheric wind profiles at the model boundary. The wind profiles are designed to have similar mean and turbulent wind properties consistent with actual site exposures.

An industry standard practice is to omit trees, vegetation, and other existing and planned landscape elements from the model due to the difficulty of providing accurate seasonal representation of vegetation. The omission of trees and other landscaping elements produces slightly more conservative (i.e., windier) wind speed values.

4.2 Wind Speed Measurements

The PLW analysis was performed by simulating wind flows and gathering velocity data over a CFD model of the site for 12 wind directions. The CFD simulation model was centered on the study building, complete with surrounding massing within a diameter of approximately 840 m.

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[1] City of Ottawa Terms of References: Wind Analysis [Undated]
https://documents.ottawa.ca/sites/default/files/torwindanalysis_en.pdf

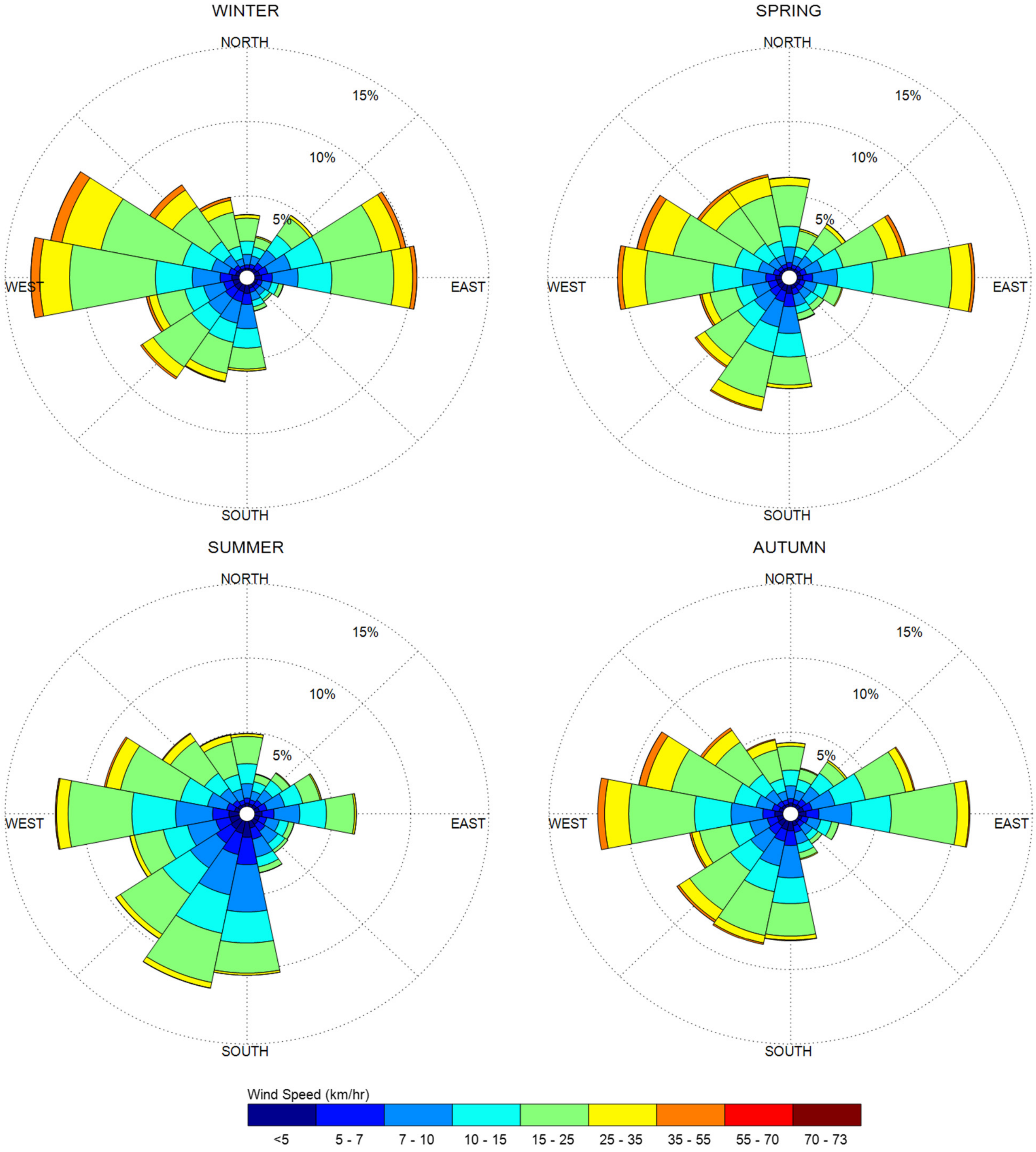
Mean and peak wind speed data obtained over the study site for each wind direction were interpolated to 36 wind directions at 10° intervals, representing the full compass azimuth. Measured wind speeds approximately 1.5 m above local grade, and 1.5 m above the amenity terrace at Level 7, were referenced to the wind speed at gradient height to generate mean and peak velocity ratios, which were used to calculate full-scale values. The gradient height represents the theoretical depth of the boundary layer of the earth's atmosphere, above which the mean wind speed remains constant. Appendices A and B provide greater detail of the theory behind wind speed measurements.

4.3 Meteorological Data Analysis

A statistical model for winds in Ottawa was developed from approximately 40-years of hourly meteorological wind data recorded at Macdonald-Cartier International Airport and obtained from Environment and Climate Change Canada. Wind speed and direction data were analyzed for each month of the year in order to determine the statistically prominent wind directions and corresponding speeds, and to characterize similarities between monthly weather patterns. Based on this portion of analysis, the four seasons are represented by grouping data from consecutive months based on similarity of weather patterns, and not according to the traditional calendar method.

The statistical model of the Ottawa area wind climate, which indicates the directional character of local winds on a seasonal basis, is illustrated on the following page. The plots illustrate seasonal distribution of measured wind speeds and directions in kilometers per hour (km/h). Probabilities of occurrence of different wind speeds are represented as stacked polar bars in sixteen azimuth divisions. The radial direction represents the percentage of time for various wind speed ranges per wind direction during the measurement period. The preferred wind speeds and directions can be identified by the longer length of the bars. For Ottawa, the most common winds occur for westerly wind directions, followed by those from the east, while the most common wind speeds are below 36 km/h. The directional preference and relative magnitude of wind speed changes somewhat from season to season.

SEASONAL DISTRIBUTION OF WINDS FOR VARIOUS DIRECTIONS
MACDONALD-CARTIER INTERNATIONAL AIRPORT, OTTAWA



Notes:

1. Radial distances indicate percentage of time of wind events.
2. Wind speeds are mean hourly in km/h, measured at 10 m above the ground.

4.4 Pedestrian Comfort and Safety Criteria – City of Ottawa

Pedestrian comfort and safety criteria are based on the mechanical effects of wind without consideration of other meteorological conditions (i.e., temperature, relative humidity). The comfort guidelines assume that pedestrians are appropriately dressed for a specified outdoor activity during any given season. Five pedestrian comfort classes are based on 80% non-exceedance mean wind speed ranges, which include (1) Sitting; (2) Standing; (3) Strolling; (4) Walking; and (5) Uncomfortable. More specifically, the comfort classes and associated mean wind speed ranges are summarized as follows:

1) **Sitting:** Mean wind speeds no greater than 10 km/h occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 16 km/h.

2) **Standing:** Mean wind speeds no greater than 14 km/h occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 22 km/h.

3) **Strolling:** Mean wind speeds no greater than 17 km/h occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 27 km/h.

4) **Walking:** Mean wind speeds no greater than 20 km/h occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 32 km/h.

5) **Uncomfortable:** Uncomfortable conditions are characterized by predicted values that fall below the 80% target for walking. Brisk walking and exercise, such as jogging, would be acceptable for moderate excesses of this criterion.

The pedestrian safety wind speed criterion is based on the approximate threshold that would cause a vulnerable member of the population to fall. A 0.1% exceedance gust wind speed of 90 km/h is classified as dangerous. The gust speeds, and equivalent mean speeds, are selected based on 'The Beaufort Scale', presented on the following page, which describes the effects of forces produced by varying wind speed levels on objects. Gust speeds are included because pedestrians tend to be more sensitive to wind gusts than to steady winds for lower wind speed ranges. For strong winds approaching dangerous levels, this effect is less important because the mean wind can also create problems for pedestrians. The mean gust speed ranges are selected based on 'The Beaufort Scale', which describes the effect of forces produced by varying wind speeds on levels on objects.

THE BEAUFORT SCALE

Number	Description	Wind Speed (Km/h)	Description
2	Light Breeze	4-8	Wind felt on faces
3	Gentle Breeze	8-15	Leaves and small twigs in constant motion; Wind extends light flags
4	Moderate Breeze	15-22	Wind raises dust and loose paper; Small branches are moved
5	Fresh Breeze	22-30	Small trees in leaf begin to sway
6	Strong Breeze	30-40	Large branches in motion; Whistling heard in electrical wires; Umbrellas used with difficulty
7	Moderate Gale	40-50	Whole trees in motion; Inconvenient walking against wind
8	Gale	50-60	Breaks twigs off trees; Generally impedes progress

Experience and research on people's perception of mechanical wind effects has shown that if the wind speed levels are exceeded for more than 80% of the time, the activity level would be judged to be uncomfortable by most people. For instance, if a mean wind speed of 10 km/h (gust equivalent mean wind speed of 16 km/h) was exceeded for more than 20% of the time most pedestrians would judge that location to be too windy for sitting. Similarly, if mean wind speed of 20 km/h (gust equivalent mean wind speed of 32 km/h) at a location were exceeded for more than 20% of the time, walking or less vigorous activities would be considered uncomfortable. As most of these criteria are based on subjective reactions of a population to wind forces, their application is partly based on experience and judgment.

Once the pedestrian wind speed predictions have been established at tested locations, the assessment of pedestrian comfort involves determining the suitability of the predicted wind conditions for their associated spaces. This step involves comparing the predicted comfort class to the desired comfort class, which is dictated by the location type represented by the sensor (i.e., a sidewalk, building entrance, amenity space, or other). An overview of common pedestrian location types and their desired comfort classes are summarized on the following page.

DESIRED PEDESTRIAN COMFORT CLASSES FOR VARIOUS LOCATION TYPES

Location Types	Desired Comfort Classes
Major Building Entrances	Standing
Secondary Building Access Points	Walking
Primary Public Sidewalks	Strolling
Secondary Public Sidewalks / Bicycle Paths	Walking
Outdoor Amenity Spaces	Sitting / Standing / Strolling
Cafés / Patios / Benches / Gardens	Sitting
Transit Shelters	Standing
Public Parks / Plazas	Standing / Strolling
Garage / Service Entrances	Walking
Parking Lots	Strolling / Walking
Vehicular Drop-Off Zones	Standing / Strolling / Walking

5. RESULTS AND DISCUSSION

The foregoing discussion of predicted pedestrian wind conditions is accompanied by Figures 3A-6B (following the main text) illustrating the seasonal wind conditions at grade level and within the common amenity terrace at Level 7. The colour contours indicate various comfort classes predicted for certain regions. Wind conditions comfortable for sitting or more sedentary activities are represented by the colour green, standing are represented by yellow, strolling by orange, and conditions suitable for walking are represented by blue. The colour magenta represents wind conditions considered uncomfortable for walking. The common wind events are discussed as follows.

5.1 Common Wind Events

Following the introduction of the subject site, wind conditions around the development are predicted to be mixed between calm and moderately windy. Wind comfort at grade level is summarized below for each seasonal period.

- Spring Season: Wind conditions are predicted to be suitable for a mix of standing and strolling, while the sidewalk along Carling Avenue is mostly suitable for standing (Figure 3A).

- Summer Season: Conditions are predicted to be mostly suitable for sitting, with standing conditions predicted to occur at the northeast corner of the site, and along the west side of the site (Figure 4A).

- Autumn Season: Conditions are similar to those predicted during the spring season, but somewhat calmer as a function of the historical climate data (Figure 5A).

- Winter Season: Conditions are similar to those predicted during the spring season, but moderately windier, inclusive of the northwest corner of the site which is predicted to be suitable for walking (Figure 6A).

The site is impacted by most prominent winds, with particular importance assigned to easterly clockwise to northerly directions. While wind speeds are predicted to satisfy the sitting and standing comfort classes for most pedestrian areas, wind channelling is predicted to impact the driveway along the west side of the site for many wind directions. Since wind comfort is predicted be suitable for walking or better within this area, the area, conditions within this area, as well as those across the subject site at grade level, are considered acceptable throughout the year. As a general note, conditions are calmer immediately adjacent to the subject building as compared to those at greater distances from the subject building which the above summary is based.

5.2 Wind Comfort Conditions – Level 7 Amenity Terrace

The following discussion is focused on the amenity terrace situated atop the podium roof at Level 7 and to the east of the main building. The noted terrace is predicted to be moderately windy; pedestrian wind comfort is summarized below for each seasonal period. Figures 7A-7D represent a refined sitting comfort class, for each seasonal period, to illustrate the percentage of time the terrace will be suitable for sitting during each seasonal period.

- Spring Season: Conditions are predicted to be mostly suitable for a mix of standing and strolling, with the northwest corner of the terrace becoming suitable for walking. Uncomfortable conditions are also predicted to occur close to the guardrail. According to the results presented in Figure 7A, sitting conditions are predicted for at least 50% of the time during the spring.

- Summer Season: Conditions are largely suitable for standing, while strolling conditions are predicted within the northwest corner of the terrace. According to the results presented in Figure 7B, sitting conditions are predicted for at least 70% of the time during the summer season over most of the area.

- Autumn Season: Conditions are similar to those predicted during the spring season, but somewhat calmer. Furthermore, according to the results presented in Figure 7C, sitting conditions are predicted for at least 60% of the time during the autumn season.

- Winter Season: Conditions are similar to those predicted during the spring season, but windier within the northwest corner of the roof. According to the results presented in Figure 7D, sitting conditions are also predicted for at least 50% of the time during the winter season over most of the roof area.

Given the strong wind flows at the northwest corner of the roof, and the predicted comfort conditions within the remaining accessible areas, as noted above, we recommend replacing the standard height perimeter guardrail with a glass wind screen at a height no less than 2.4 m as measured from the walking surface of the roof. A canopy extending no less than 3 m outward from the east façade of the building would also further protect pedestrians from the effects of downwash winds incident on the building. It would also be beneficial to shift the terrace south, towards the centre of the roof, thereby creating a buffer between the amenity area and the north perimeter of the roof. Additional simulations will be required to confirm the effectiveness of the preferred mitigation strategy, which will be performed during design development.

5.3 Extreme Wind Events

Figures 8A and 8B present extreme wind events over a small region of the amenity terrace at Level 7 considered to be dangerous for the more susceptible pedestrians. Figure 8A illustrates the area where gust wind speeds are predicted to exceed 90 km/h for more than 0.1% of the time (or 9 hours on an annual basis), identified by the colour red. In Figure 8B, the subject area is magnified for clarity. As noted previously, 0.1% (identified by the colour dark blue) represents the cut off above which conditions are considered unsafe.

A small area along the north side of the amenity terrace is impacted close to where the tower meets the podium. The strong winds are a function of the suburban exposures surrounding the subject site, the massing of the proposed building itself, and the orientation of the building to the prominent winds. The predicted peak value is 0.16% of the time or equivalently approximately 14 hours on an annual basis, which exceeds the noted criterion by 0.06% (approximately 5 hours). The intensity of the wind is expected to be reduced to safe levels following adoption of the recommended mitigation outlined in Section 5.2.

5.4 Influence of the Proposed Development on Existing Wind Conditions

Wind conditions over surrounding sidewalks beyond the development site, as well as at nearby primary building entrances, will be acceptable for their intended pedestrian uses during each seasonal period upon the introduction of the subject site. Pedestrian wind comfort and safety have been quantified for the specific configuration of existing and foreseeable construction around the study site. Future changes (i.e., construction or demolition) of these surroundings may cause changes to the wind effects in two ways, namely: (i) changes beyond the immediate vicinity of the site would alter the wind profile approaching the site; and (ii) development in proximity to the site would cause changes to local flow patterns. More specifically, development in urban centers generally creates reduction in the mean wind and localized increases in the gustiness of the wind.

6. CONCLUSIONS AND RECOMMENDATIONS

A complete summary of the predicted wind comfort conditions is provided in Sections 5.1 and 5.2 of this report and illustrated in Figures 3A-7D following the main text, while a summary of the predicted wind safety conditions is provided in Section 5.3 and illustrated in Figures 8A and 8B for Level 7 amenity terrace.

Based on computer simulations using the CFD technique, meteorological data analysis of the Ottawa wind climate, City of Ottawa wind comfort and safety criteria, and experience with similar developments in Ottawa, we conclude the following:

1) Regarding wind comfort, conditions around the subject site at grade level are predicted to be moderately windy but nevertheless acceptable for all anticipated uses throughout the year.

2) Stronger wind conditions are predicted to occur within the amenity terrace on Level 7. To provide conditions suitable outright for sitting during the warmer months, mitigation will be required in

the form of a tall perimeter wind screen, while a canopy is also suggested to protect the roof from downwash winds incident on the building itself. It would also be beneficial to shift the terrace south, towards the centre of the roof, thereby creating a buffer between the amenity area and the north perimeter of the roof. Additional simulations will be required to confirm the effectiveness of the preferred mitigation strategy, which will be performed during design development, as noted in Section 5.2.

3) Regarding wind safety, Figures 8A and 8B present extreme wind events over a small region of the amenity terrace on Level 7 considered to be dangerous for the more susceptible pedestrians. Figure 8A illustrates the area where gust wind speeds are predicted to exceed 90 km/h for more than 0.1% of the time (or 9 hours on an annual basis). The subject area is magnified for clarity in Figure 8B. The relevant area is the north side of the terrace, close to where the tower meets the podium. The predicted peak value is 0.16% of the time or equivalently approximately 14 hours on an annual basis. The intensity of the wind is expected to be reduced to safe levels following adoption of the recommended mitigation outlined in Section 5.2.

4) Within the context of typical weather patterns, which exclude anomalous localized storm events such as tornadoes and downbursts, no areas surrounding the subject site at grade level were found to experience conditions that could be considered dangerous.

This concludes our pedestrian level wind study and report. Please advise the undersigned of any questions or comments.

Sincerely,

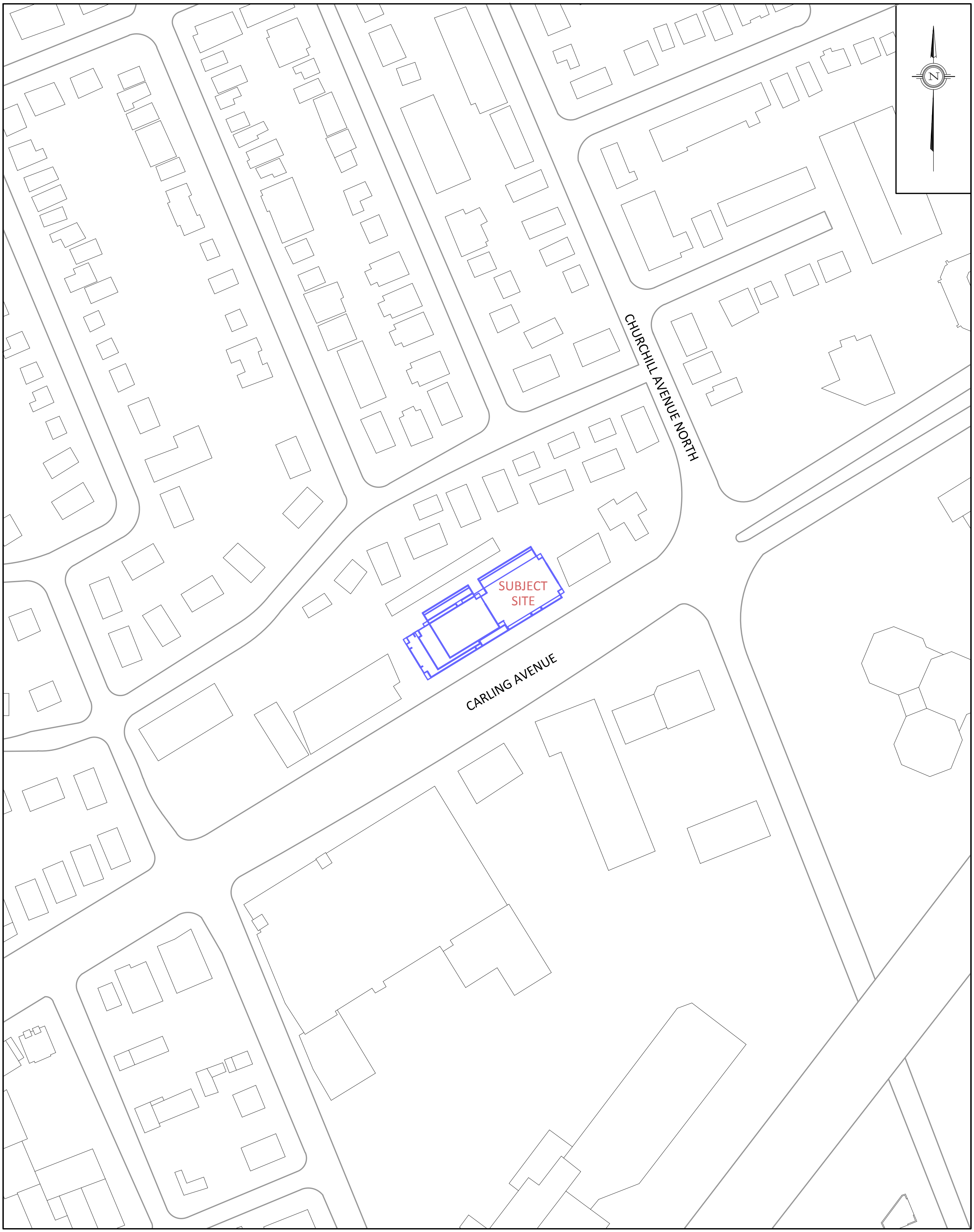
Gradient Wind Engineering Inc.

E. Urbanski
Edward Urbanski, M.Eng.
Junior Wind Scientist

LICENSED PROFESSIONAL ENGINEER
J. D. FERRARO
100158495
Oct. 10, 2019
PROVINCE OF ONTARIO

Justin Ferraro, P.Eng.
Principal

Gradient Wind File #19-192



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PROJECT	1655 CARLING AVENUE, OTTAWA PEDESTRIAN LEVEL WIND STUDY		
SCALE	1:2500 (APPROX.)	DRAWING NO.	19-192-PLW-1
DATE	OCTOBER 10, 2019	DRAWN BY	C.E.

DESCRIPTION

FIGURE 1:
SITE PLAN AND SURROUNDING CONTEXT

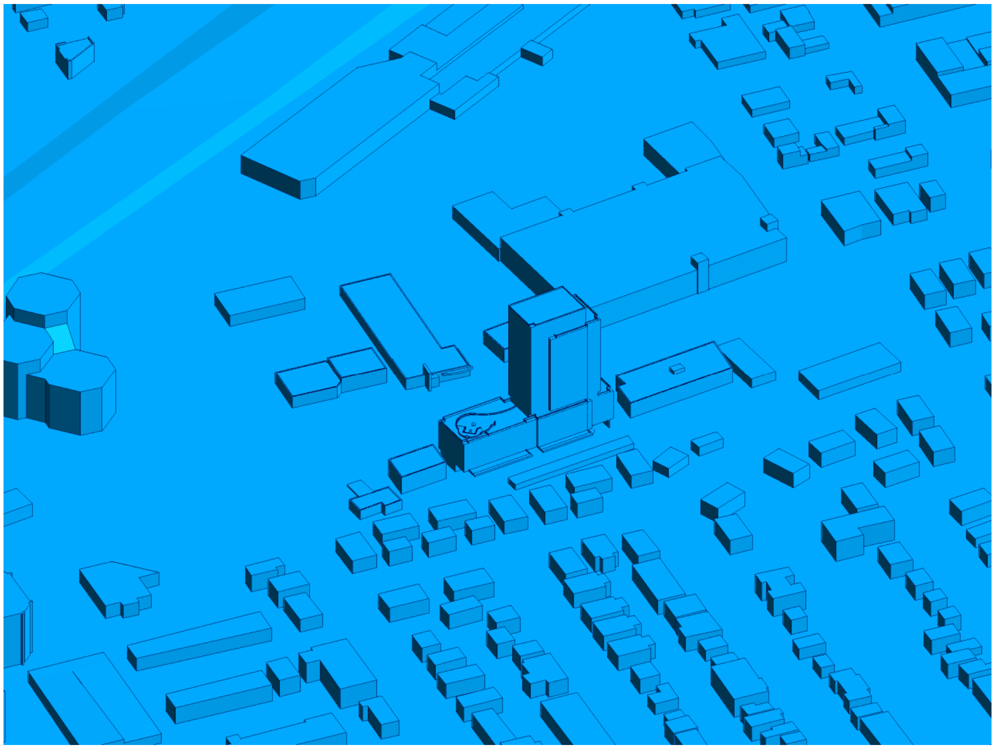

FIGURE 2A: COMPUTATIONAL MODEL, NORTH PERSPECTIVE

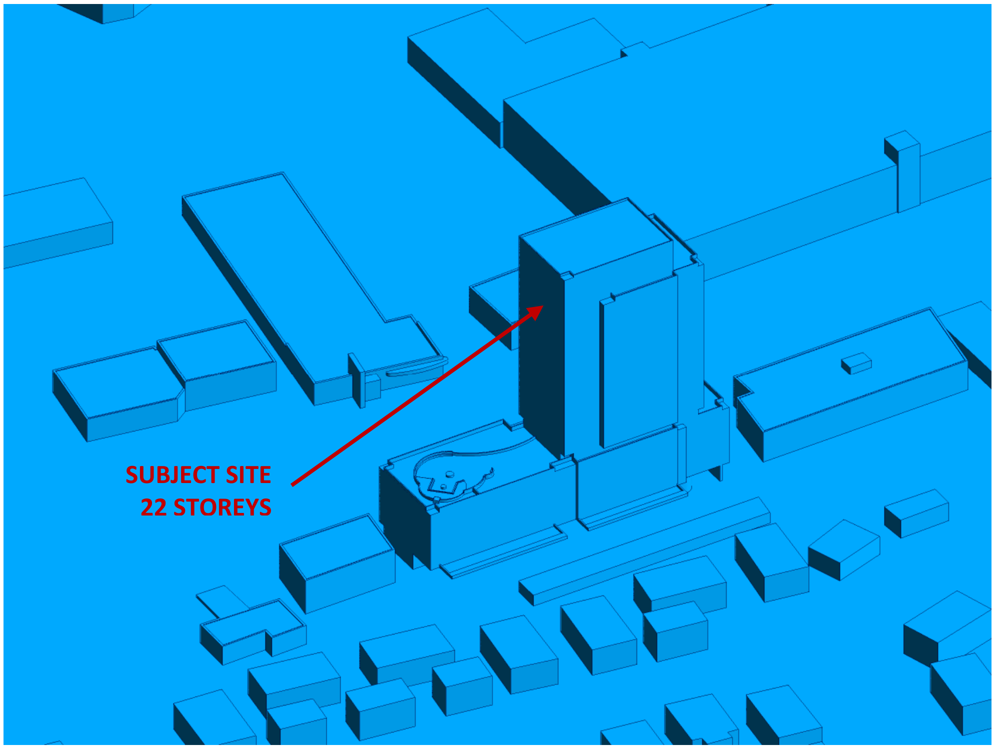

FIGURE 2B: CLOSE UP OF FIGURE 2A

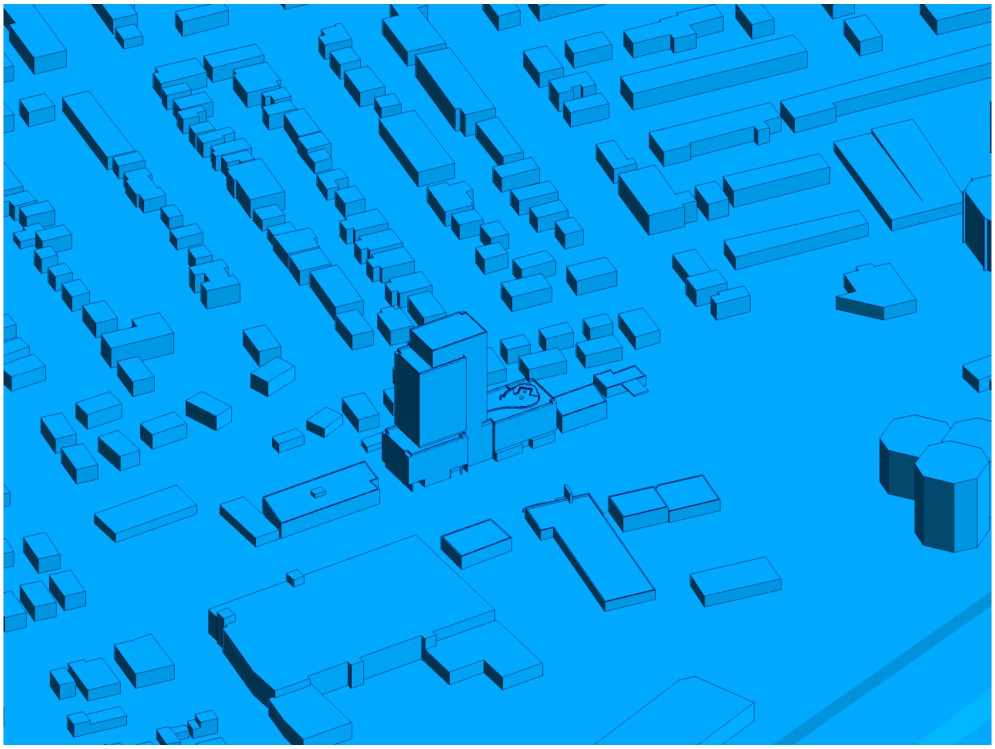

FIGURE 2C: COMPUTATIONAL MODEL, SOUTH PERSPECTIVE

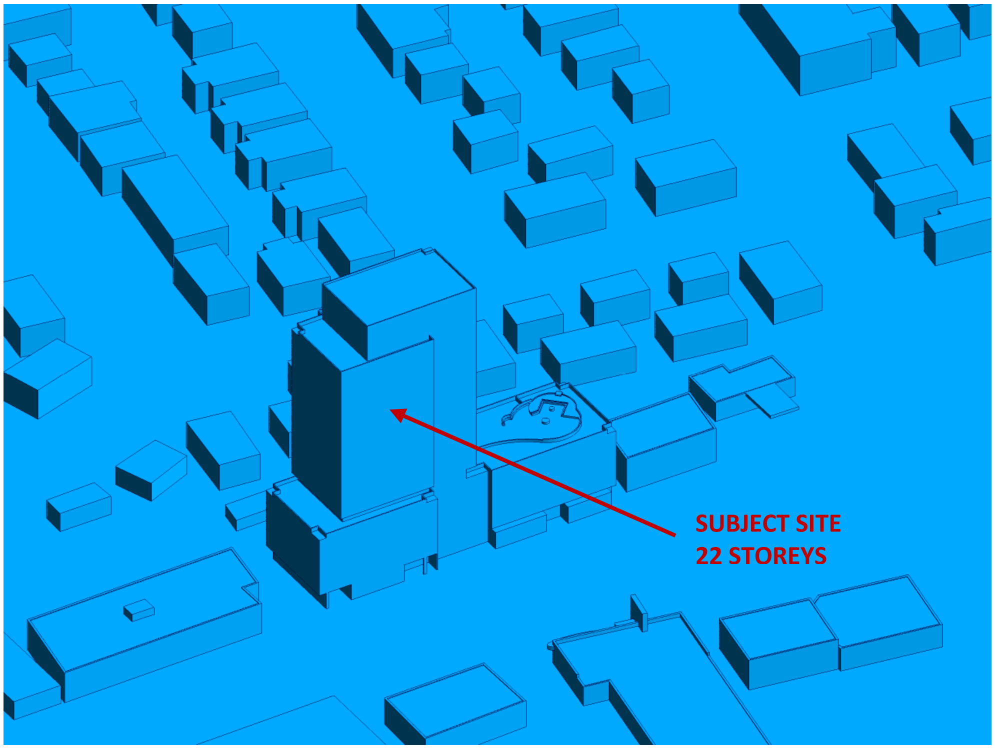

FIGURE 2D: CLOSE UP OF FIGURE 2C

FIGURE 3A: SPRING – WIND CONDITIONS AT GRADE LEVEL

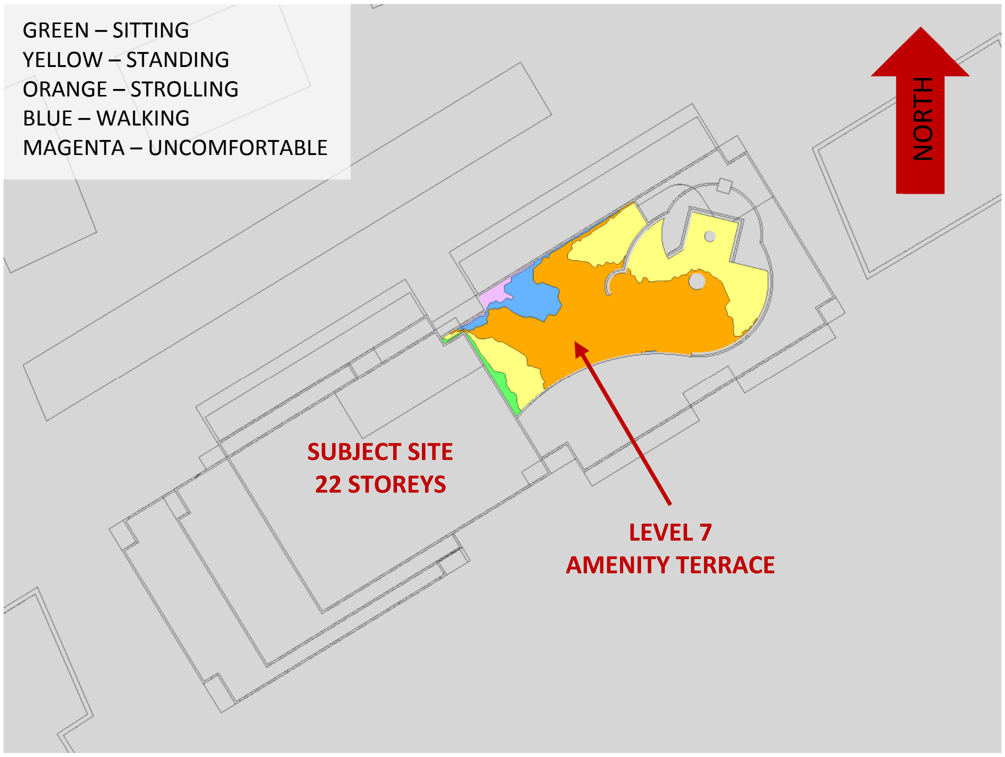

FIGURE 3B: SPRING – WIND CONDITIONS WITHIN COMMON AMENITY TERRACE

FIGURE 4A: SUMMER – WIND CONDITIONS AT GRADE LEVEL

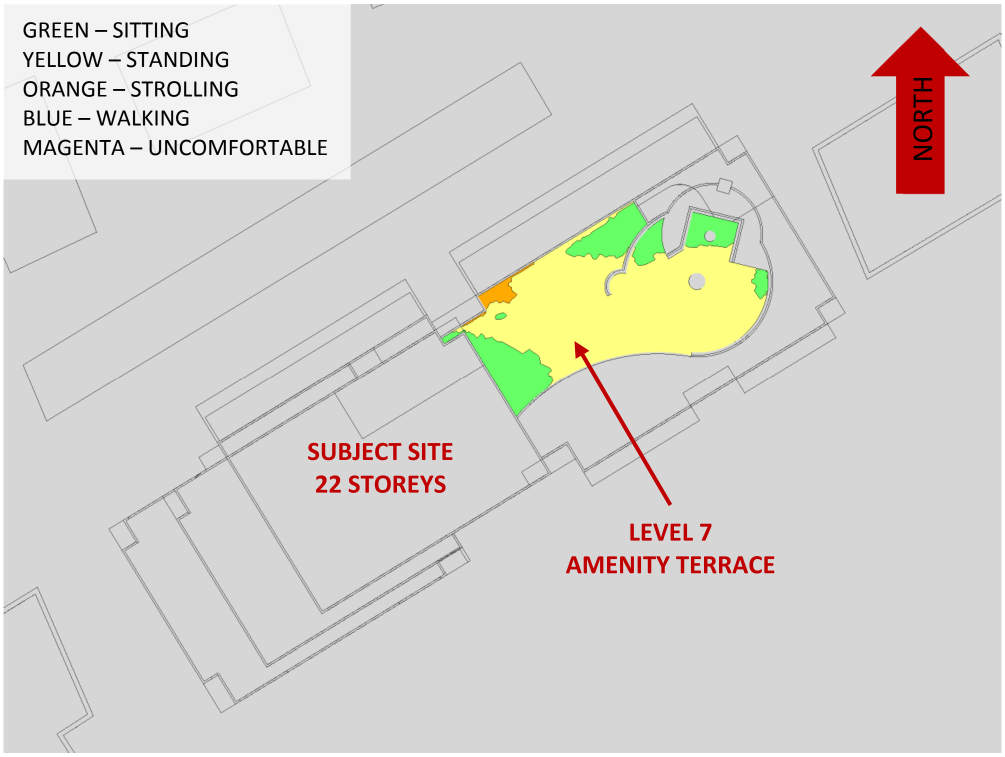

FIGURE 4B: SUMMER – WIND CONDITIONS WITHIN COMMON AMENITY TERRACE

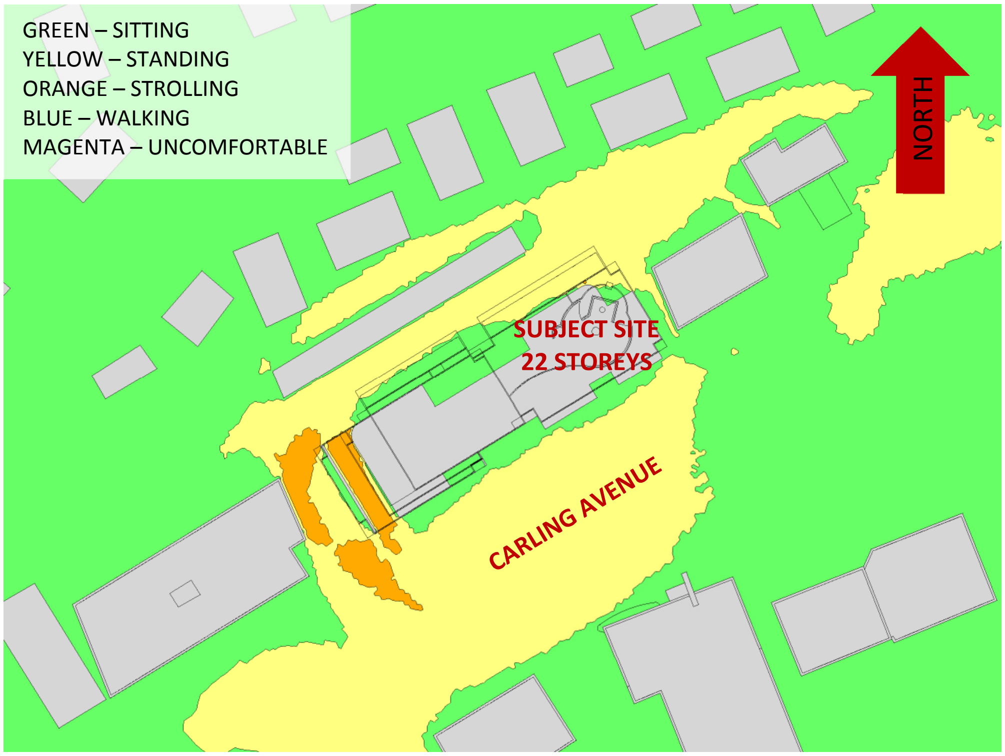

FIGURE 5A: AUTUMN – WIND CONDITIONS AT GRADE LEVEL

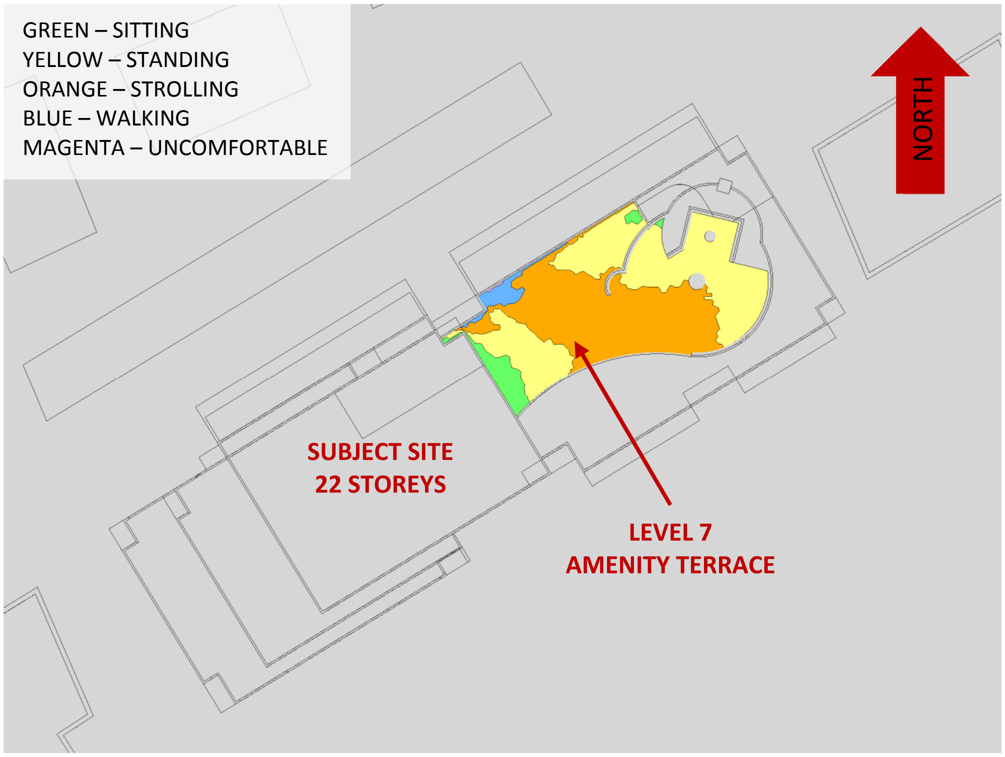

FIGURE 5B: AUTUMN – WIND CONDITIONS WITHIN COMMON AMENITY TERRACE

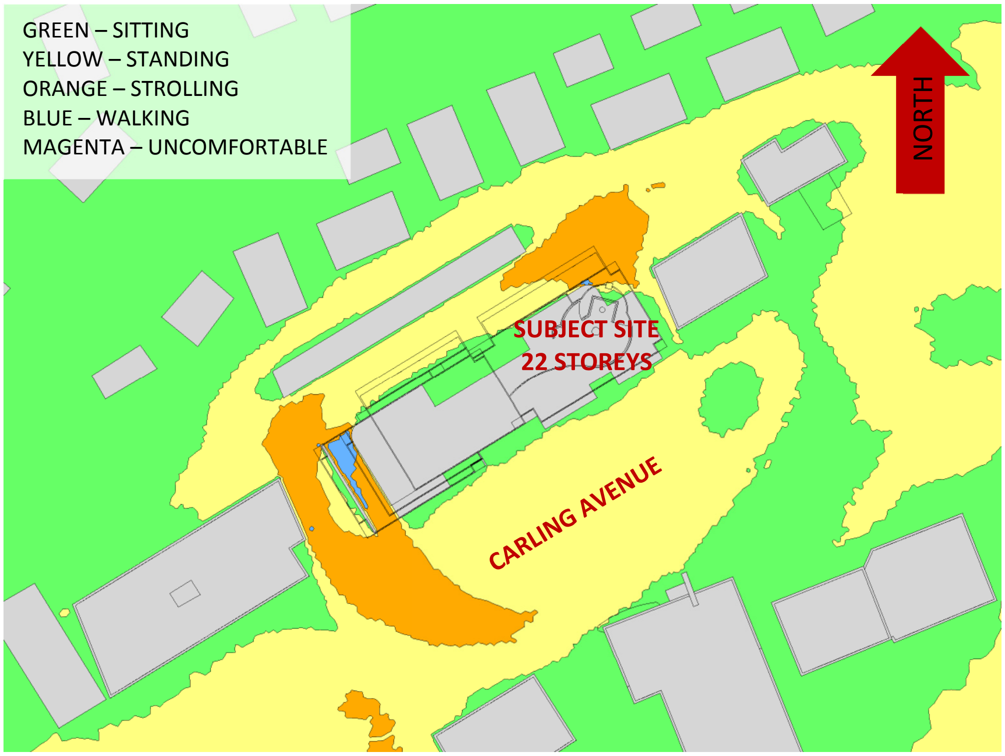

FIGURE 6A: WINTER – WIND CONDITIONS AT GRADE LEVEL

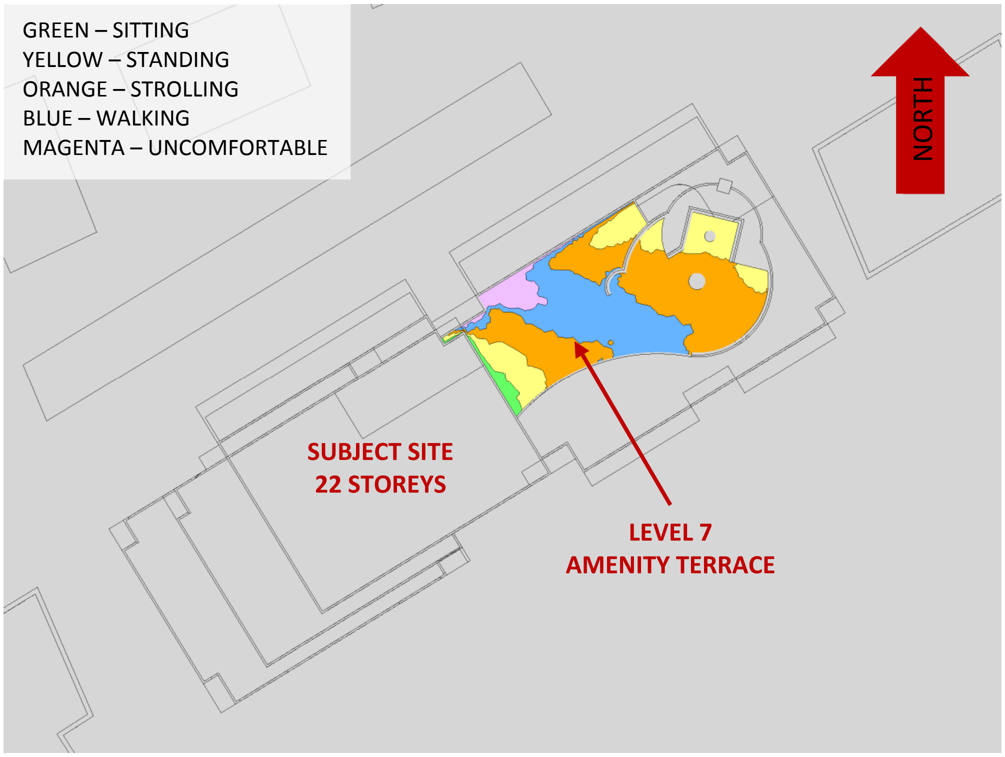

FIGURE 6B: WINTER – WIND CONDITIONS WITHIN COMMON AMENITY TERRACE

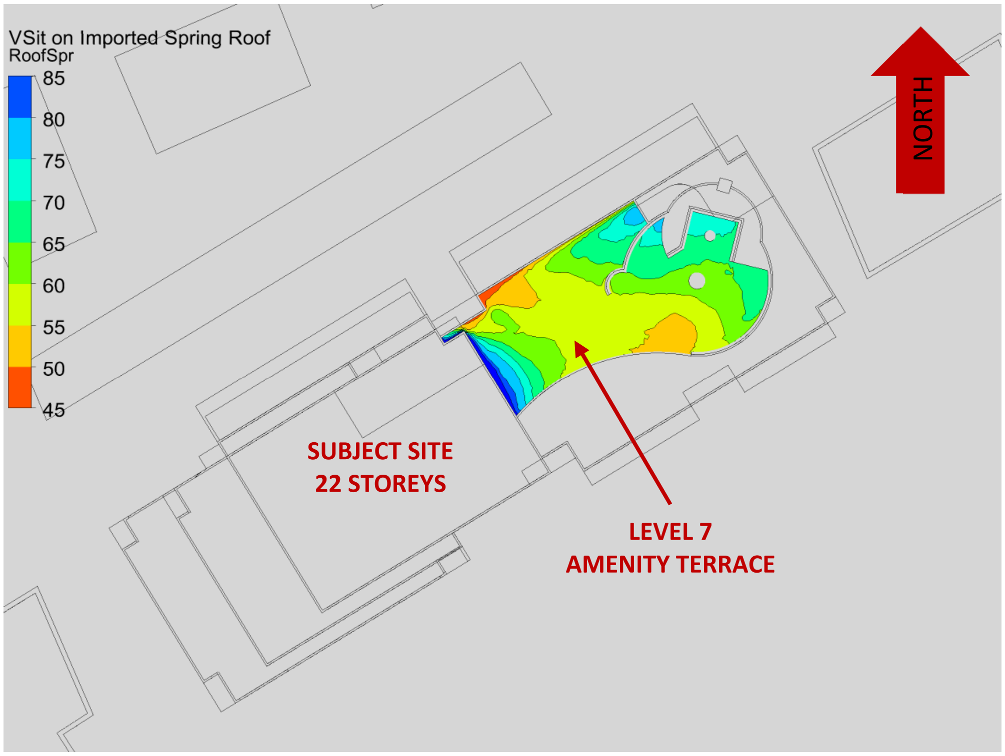

FIGURE 7A: SPRING – PERCENTAGE OF TIME SUITABLE FOR SITTING (TERRACES)

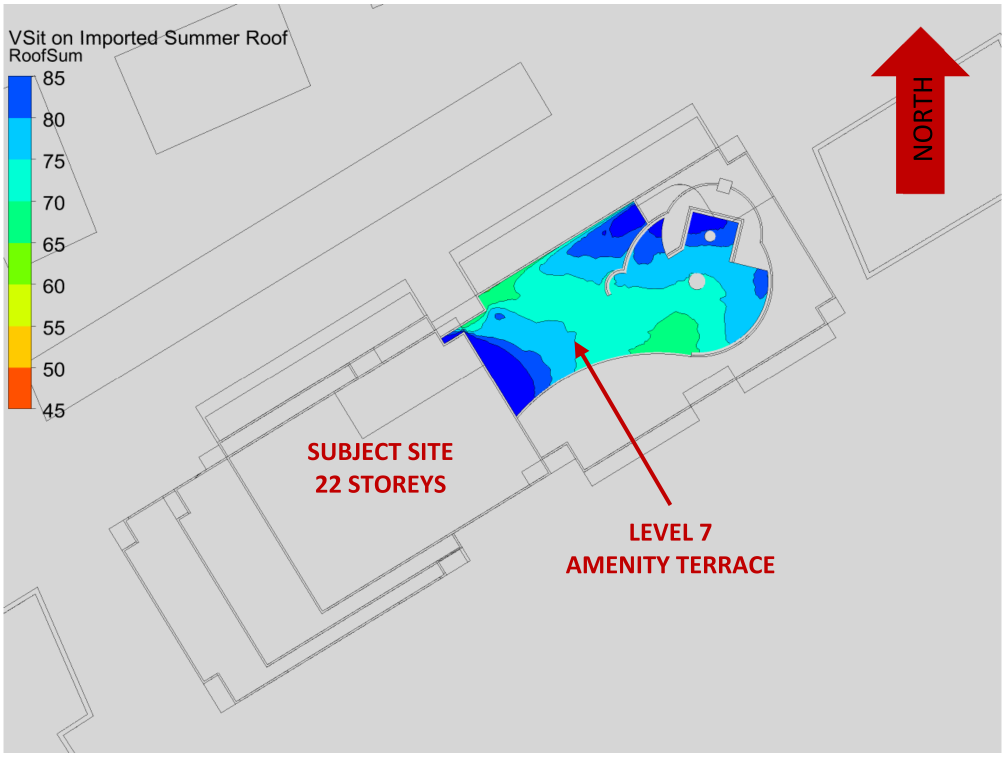

FIGURE 7B: SUMMER – PERCENTAGE OF TIME SUITABLE FOR SITTING (TERRACES)

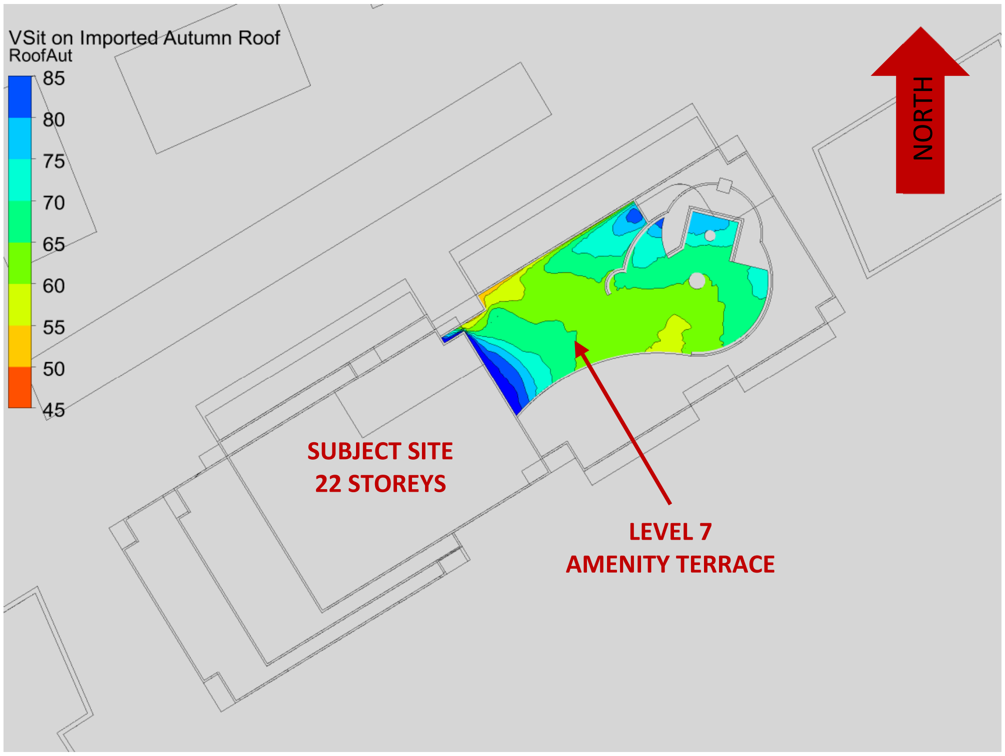

FIGURE 7C: AUTUMN – PERCENTAGE OF TIME SUITABLE FOR SITTING (TERRACES)

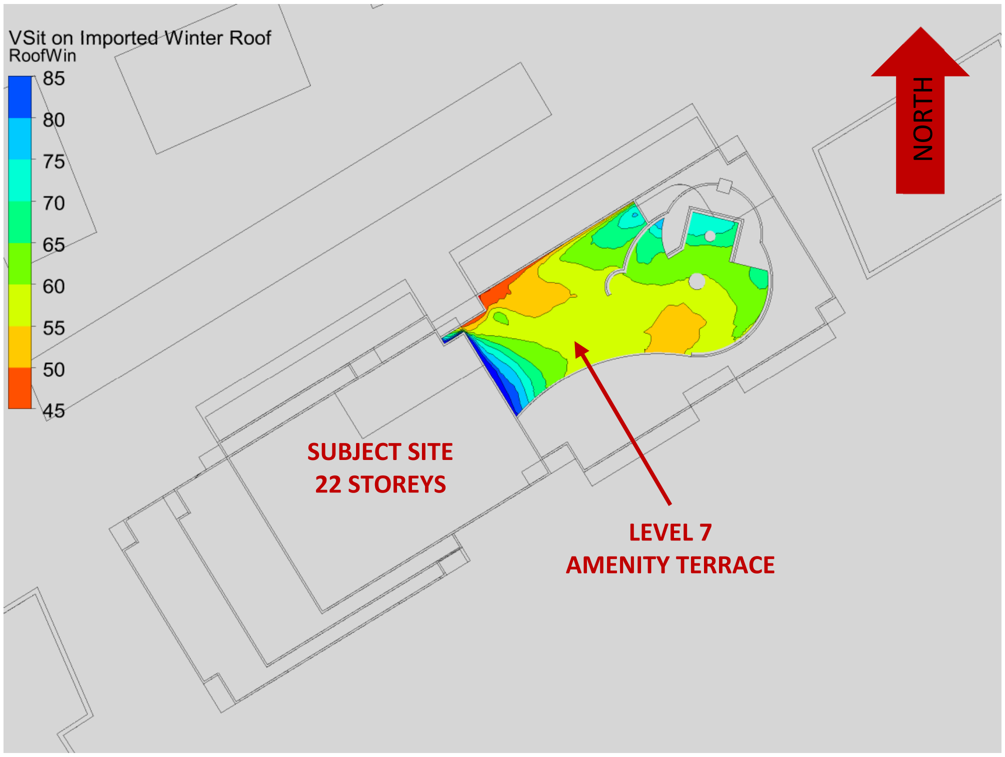

FIGURE 7D: WINTER – PERCENTAGE OF TIME SUITABLE FOR SITTING (TERRACES)

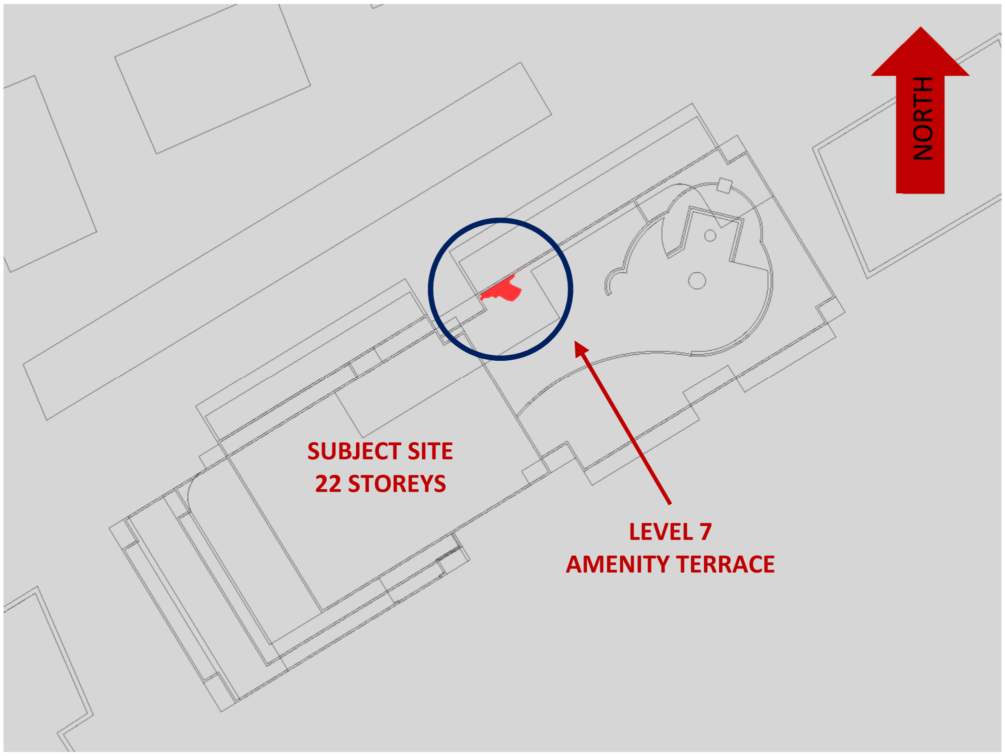

FIGURE 8A: ANNUAL WIND SAFETY – LEVEL 7 TERRACE (RED REPRESENTS 'DANGEROUS')

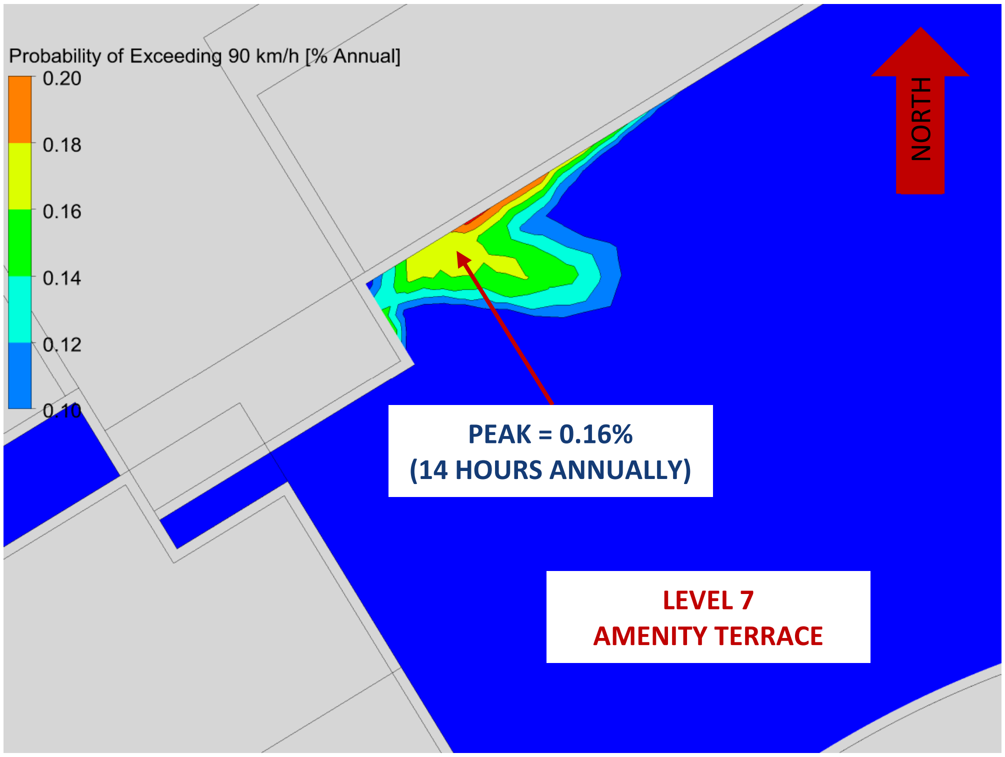

FIGURE 8B: ANNUAL WIND SAFETY – PERCENTAGE OF TIME WIND SPEED EXCEEDS 90 km/h

APPENDIX A

SIMULATION OF THE NATURAL WIND

The information contained within this appendix is offered to provide a greater understanding of the relationship between the physical wind tunnel testing method and virtual computer-based simulations

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SIMULATION OF THE NATURAL WIND

Wind flowing over the surface of the earth develops a boundary layer due to the drag produced by surface features such as vegetation and man-made structures. Within this boundary layer, the mean wind speed varies from zero at the surface to the gradient wind speed at the top of the layer. The height of the top of the boundary layer is referred to as the gradient height, above which the velocity remains more-or-less constant for a given synoptic weather system. The mean wind speed is taken to be the average value over one hour. Superimposed on the mean wind speed are fluctuating (or turbulent) components in the longitudinal (i.e. along wind), vertical and lateral directions. Although turbulence varies according to the roughness of the surface, the turbulence level generally increases from nearly zero (smooth flow) at gradient height to maximum values near the ground. While for a calm ocean the maximum could be 20%, the maximum for a very rough surface such as the center of a city could be 100%, or equal to the local mean wind speed. The height of the boundary layer varies in time and over different terrain roughness within the range of 400 metres (m) to 600 m.

Simulating real wind behaviour in a wind tunnel, or by computational simulations (CFD), requires simulating the variation of mean wind speed with height, simulating the turbulence intensity, and matching the typical length scales of turbulence. It is the ratio between wind tunnel turbulence length scales and turbulence scales in the atmosphere that determines the geometric scales that models can assume in a wind tunnel. Hence, when a 1:200 scale model is quoted, this implies that the turbulence scales in the wind tunnel and the atmosphere have the same ratios. Some flexibility in this requirement has been shown to produce reasonable wind tunnel predictions compared to full scale. In model scale the mean and turbulence characteristics of the wind are obtained with the use of spires at one end of the tunnel and roughness elements along the floor of the tunnel. The fan is located at the model end and wind is pulled over the spires, roughness elements and model. It has been found that, to a good approximation, the mean wind profile can be represented by a power law relation, shown below, giving height above ground versus wind speed.

$$U = U_g \left(\frac{Z}{Z_g} \right)^{\alpha}$$

Where; ***U*** = mean wind speed, $\boldsymbol{U_g}$ = gradient wind speed, ***Z*** = height above ground, $\boldsymbol{Z_g}$ = depth of the boundary layer (gradient height) and α is the power law exponent.

Figure A1 on the following page plots three velocity profiles for open country, and suburban and urban exposures. The exponent α varies according to the type of upwind terrain; α ranges from 0.14 for open country to 0.33 for an urban exposure. Figure A2 illustrates the theoretical variation of turbulence for open country, suburban and urban exposures.

The integral length scale of turbulence can be thought of as an average size of gust in the atmosphere. Although it varies with height and ground roughness, it has been found to generally be in the range of 100 m to 200 m in the upper half of the boundary layer. Thus, for a 1:300 scale, the model value should be between 1/3 and 2/3 of a metre. Integral length scales are derived from power spectra, which describe the energy content of wind as a function of frequency. There are several ways of determining integral length scales of turbulence. One way is by comparison of a measured power spectrum in model scale to a non-dimensional theoretical spectrum such as the Davenport spectrum of longitudinal turbulence. Using the Davenport spectrum, which agrees well with full-scale spectra, one can estimate the integral scale by plotting the theoretical spectrum with varying L until it matches as closely as possible the measured spectrum:

$$f \times S(f) = \frac{\dfrac{4(Lf)^2}{U_{10}{}^2}}{\left[1 + \dfrac{4(Lf)^2}{U_{10}{}^2}\right]^{\frac{4}{3}}}$$

Where, f is frequency, S(f) is the spectrum value at frequency f, U10 is the wind speed 10 m above ground level, and L is the characteristic length of turbulence.

Once the wind simulation is correct, the model, constructed to a suitable scale, is installed at the centre of the working section of the wind tunnel. Different wind directions are represented by rotating the model to align with the wind tunnel center-line axis.

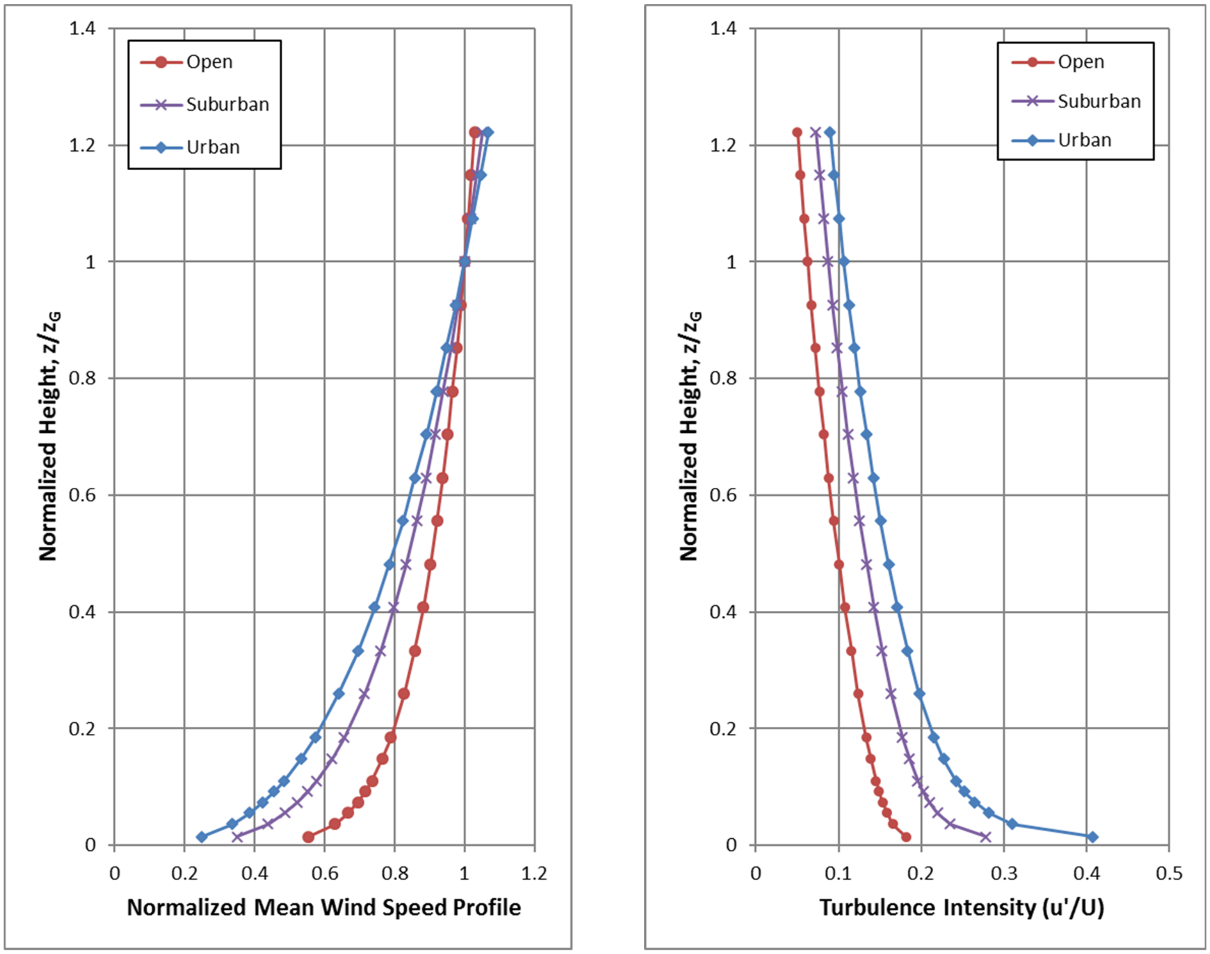

FIGURE A1 (LEFT): MEAN WIND SPEED PROFILES;
FIGURE A2 (RIGHT): TURBULENCE INTENSITY PROFILES

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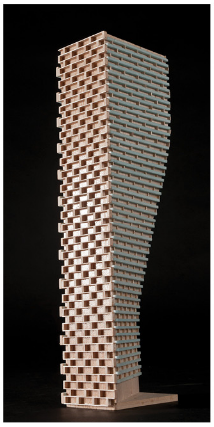

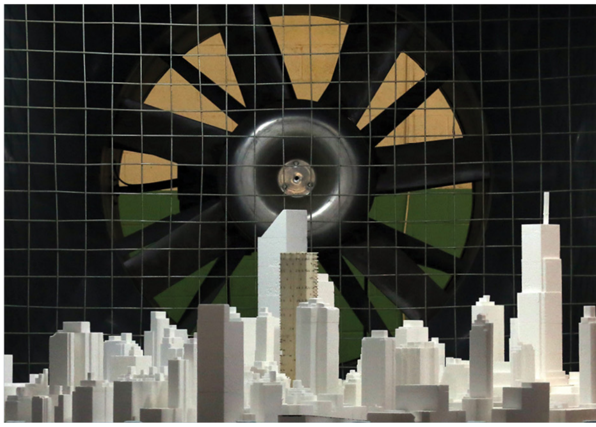

APPENDIX B

PEDESTRIAN LEVEL WIND MEASUREMENT METHODOLOGY

The information contained within this appendix is offered to provide a greater understanding of the relationship between the physical wind tunnel testing method and virtual computer-based simulations

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PEDESTRIAN LEVEL WIND MEASUREMENT METHODOLOGY

Pedestrian level wind studies are performed in a wind tunnel on a physical model of the study buildings at a suitable scale. Instantaneous wind speed measurements are recorded at a model height corresponding to 1.5 m full scale using either a hot wire anemometer or a pressure-based transducer. Measurements are performed at any number of locations on the model and usually for 36 wind directions. For each wind direction, the roughness of the upwind terrain is matched in the wind tunnel to generate the correct mean and turbulent wind profiles approaching the model.

The hot wire anemometer is an instrument consisting of a thin metallic wire conducting an electric current. It is an omni-directional device equally sensitive to wind approaching from any direction in the horizontal plane. By compensating for the cooling effect of wind flowing over the wire, the associated electronics produce an analog voltage signal that can be calibrated against velocity of the air stream. For all measurements, the wire is oriented vertically so as to be sensitive to wind approaching from all directions in a horizontal plane.

The pressure sensor is a small cylindrical device that measures instantaneous pressure differences over a small area. The sensor is connected via tubing to a transducer that translates the pressure to a voltage signal that is recorded by computer. With appropriately designed tubing, the sensor is sensitive to a suitable range of fluctuating velocities.

For a given wind direction and location on the model, a time history of the wind speed is recorded for a period of time equal to one hour in full-scale. The analog signal produced by the hot wire or pressure sensor is digitized at a rate of 400 samples per second. A sample recording for several seconds is illustrated in Figure B1. This data is analyzed to extract the mean, root-mean-square (rms) and the peak of the signal. The peak value, or gust wind speed, is formed by averaging a number of peaks obtained from sub-intervals of the sampling period. The mean and gust speeds are then normalized by the wind tunnel gradient wind speed, which is the speed at the top of the model boundary layer, to obtain mean and gust ratios. At each location, the measurements are repeated for 36 wind directions to produce normalized polar plots, which will be provided upon request.

In order to determine the duration of various wind speeds at full scale for a given measurement location the gust ratios are combined with a statistical (mathematical) model of the wind climate for the project site. This mathematical model is based on hourly wind data obtained from one or more meteorological stations (usually airports) close to the project location. The probability model used to represent the data is the Weibull distribution expressed as:

$$P\left(>U_g\right) = A_\theta \bullet \exp\left[\left(-\frac{U_g}{C_\theta}\right)^{K\theta}\right]$$

Where,

P (> U_g***)*** is the probability, fraction of time, that the gradient wind speed U_g is exceeded; θ is the wind direction measured clockwise from true north, ***A***, ***C***, ***K*** are the Weibull coefficients, (Units: A - dimensionless, C - wind speed units [km/h] for instance, K - dimensionless). A_θ is the fraction of time wind blows from a 10° sector centered on θ.

Analysis of the hourly wind data recorded for a length of time, on the order of 10 to 30 years, yields the A_θ, C_θ and K_θ values. The probability of exceeding a chosen wind speed level, say 20 km/h, at sensor *N* is given by the following expression:

$$P_N(>\ 20) = \Sigma_\theta P\left[\frac{(>\ 20)}{\left(\frac{U_N}{U_g}\right)}\right]$$

$$P_N(>20) \quad = \quad \Sigma_\theta P\{>20/(U_N/U_g)\}$$

Where, U_N/U_g is the gust velocity ratios, where the summation is taken over all 36 wind directions at 10° intervals.

If there are significant seasonal variations in the weather data, as determined by inspection of the C_θ and K_θ values, then the analysis is performed separately for two or more times corresponding to the groupings of seasonal wind data. Wind speed levels of interest for predicting pedestrian comfort are based on the comfort guidelines chosen to represent various pedestrian activity levels as discussed in the main text.

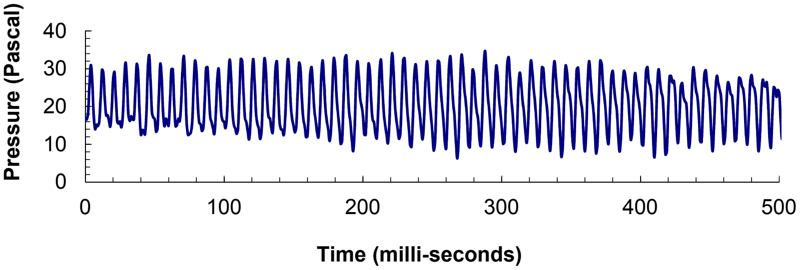

FIGURE B1: TIME VERSUS VELOCITY TRACE FOR A TYPICAL WIND SENSOR

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