GRADIENT WIND
ENGINEERING INC

Pedestrian Level Wind Study

145 Loretta Avenue & 951 Gladstone Avenue

Ottawa, Ontario

REPORT: GWE18-075-CFDPLW

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October 18, 2018

EXECUTIVE SUMMARY

This report describes a computer-based pedestrian level wind study in support of a Zoning By-law Amendment (ZBA) for the proposed mixed-use development at 145 Loretta Avenue and 951 Gladstone Avenue in Ottawa, Ontario. 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. The results and recommendations derived from these considerations are summarized in the following paragraphs and detailed in the subsequent report.

This study is based on industry standard CFD simulation and data analysis procedures, architectural drawings provided by Hobin Architecture Incorporated in September 2018, surrounding street layouts and existing and approved future building massing information obtained from the City of Ottawa, as well as recent site imagery.

A complete summary of the predicted wind conditions across the study site is presented in Section 5 of this report. Based on CFD test results, interpretation, and experience with similar developments, we conclude the following:

i. The majority of grade-level areas within and surrounding the development site will be acceptable for the intended pedestrian uses on a seasonal basis. More specifically, surrounding sidewalks, exterior amenity areas and building access points will experience acceptable wind conditions throughout the year.

ii. If designated seating areas will be provided along the pathway located northeast of the development, it is recommended to introduce localized wind barriers rising 1.8 metres above the walking surface to shield from northwesterly wind directions.

iii. If the bus stop at the northeast corner of Lorretta Avenue and Gladstone Avenue will be maintained once the proposed building is in place, it is recommended to install a bus shelter to provide relief from oncoming winds.

iv. For the 7th floor terrace over the podium rooftop of Tower 1, it is recommended that 2.0 metre-tall high-solidity wind barriers be installed along the perimeter of the terrace, in addition to localized wind barriers rising 1.8 metres in certain areas designated for seating, to shield from west quadrant winds.

v. For the 2nd floor rooftop terraces between Towers 1 and 2, as well as between Towers 2 and 3, it is recommended that 1.8 metre-tall high-solidity wind barriers be installed along the perimeter of the terraces to ensure conditions will be suitable for sitting or more sedentary activities during the typical use period.

vi. Excluding anomalous localized storm events such as tornadoes and downbursts, no areas over the study site are considered unsafe.

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1. INTRODUCTION

Gradient Wind Engineering Inc. (GWE) was retained by Trinity Development Group Inc. to undertake a computer-based pedestrian level wind (PLW) study for the proposed mixed-use development at 145 Loretta Avenue and 951 Gladstone Avenue in Ottawa, Ontario. Our mandate within this study, as outlined in GWE proposal #GWE18-074P, dated March 16, 2018, is to investigate pedestrian wind comfort within and surrounding the development 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 CFD simulation and data analysis procedures, architectural drawings provided by Hobin Architecture Incorporated in September 2018, 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 proposed development is located at 145 Loretta Avenue and 951 Gladstone Avenue in Ottawa, Ontario. The subject site is situated on a triangular parcel of land bounded by Loretta Avenue North to the west, the O-Train Confederation line to the northeast, and Gladstone Avenue to the south. The development is situated on uneven topography that gently slopes downward to the east. A future green space, including a multi-use pathway, is planned along the east side of the site. The development is integrated with Gladstone Station by an enclosed pedestrian bridge at the southeast corner of the site, which provides access to the future O-Train Station.

The development comprises Tower 1 (40 storeys), Tower 2 (35 storeys) and Tower 3 (30 storeys), respectively located south to north on the site. Towers 2 and 3 are connected by a two-storey podium containing lobby space, while Towers 2 and 3 are connected by a covered, single-storey loading area. A grade-level terrace is located to the east side of the connection between Towers 2 and 3. Two levels of below-grade parking is accessed at the east side of the building from a driveway connecting to Gladstone Avenue. A nearly rectangular planform, six-storey office podium serving Tower 1 features retail and lobby space at grade and is integrated with the existing Standard Bread Building at the southeast corner of the site. The remaining ground floor below Towers 2 and 3 contains residential units, as well as amenity and utility spaces.

Residential units occupy the remaining floors above podium levels. The respective, typical floorplates for Towers 2 and 3 above podium level are nearly rectangular with diagonal northeast walls, with a more elongated Tower 3 planform. The Tower 1 floorplate sets back from all sides to create an outdoor amenity area at the 7th floor over the podium roof. The planform for Tower 1 is similar to Tower 2 without the northeast diagonal wall, although the Tower 1 floorplate sets back again from the east and west side at the 35th and 38th floor. Additional elevated amenity terraces are located over the connections between Towers 1 and 2, and Towers 2 and 3.

The immediate surroundings of the development site comprise of a mix of suburban and industrial low-rise developments in all directions, with an open undeveloped area northeast of the site. At greater distances from the study site, the surroundings comprise primarily of low-rise suburban developments, with LeBreton Flats followed by the Ottawa River beginning approximately 750 metres to the north, and Dow's Lake and the Central Experimental Farm beginning approximately 1 kilometre to the southeast, and the south, respectively.

Key areas under consideration for pedestrian wind comfort include surrounding sidewalks, walkways, building access points, surface parking, bus stops, the future Gladstone O-Train Station, and various grade-level and rooftop amenity spaces. Figure 1 illustrates the study site and surrounding context, while Figures 2A and 2B illustrate the computational model used to conduct the study.

3. OBJECTIVES

The principal objectives of this study are to (i) determine pedestrian level comfort and safety conditions within and surrounding the development site; (ii) identify areas where future 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 Computational Fluid Dynamics (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 industry-accepted guidelines[1]. The following sections describe the analysis procedures, including a discussion of the pedestrian comfort guidelines.

4.1 Computer-Based Context Modelling

A computer-based PLW study is 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, are 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 wind tunnel model due to the difficulty of providing accurate seasonal representation of vegetation. The omission of trees and other landscaping elements produces slightly more conservative 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 buildings, complete with surrounding massing within a diameter of approximately 822 metres.

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 metres above local grade 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.

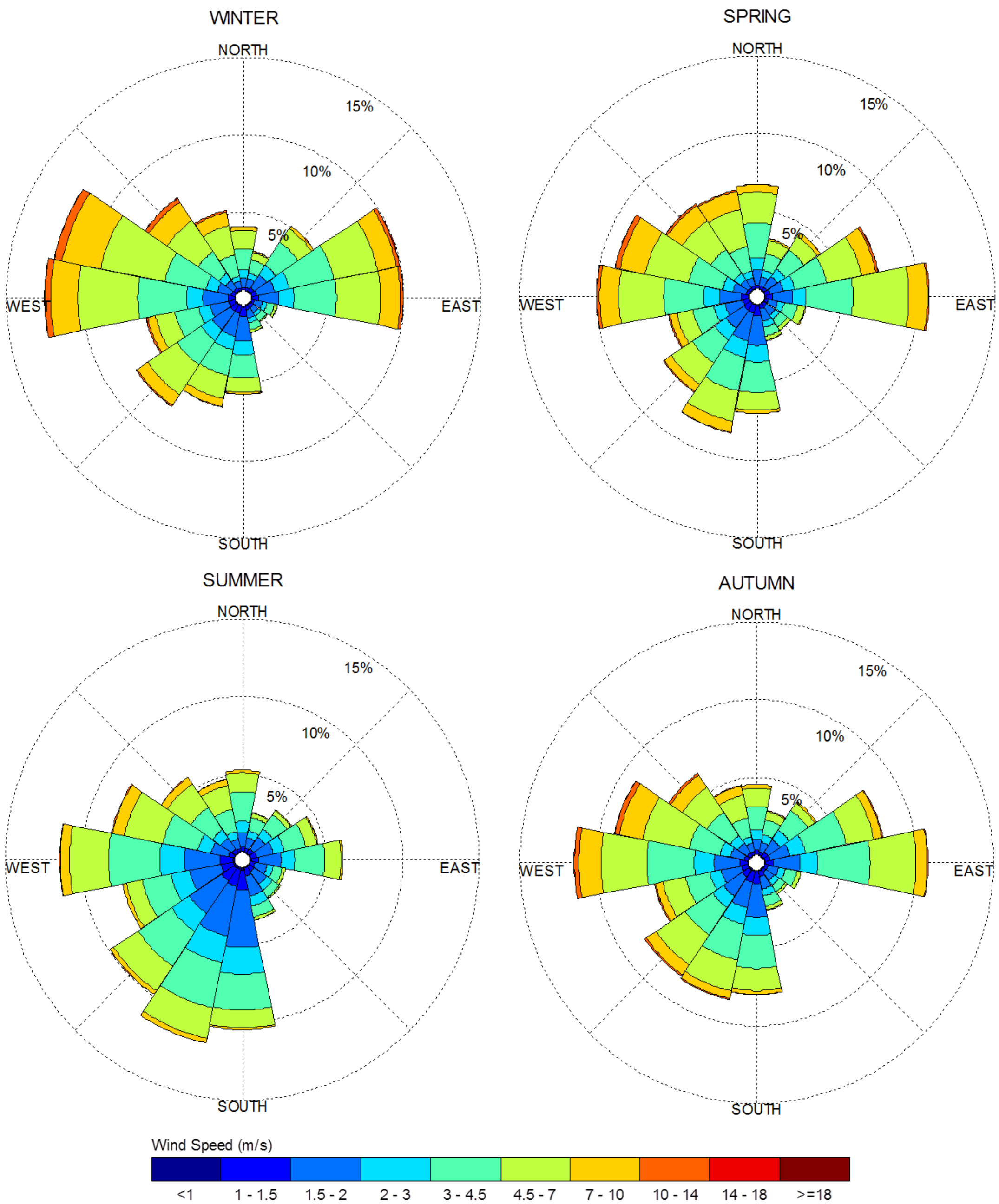
[1] City of Ottawa Terms of References: Wind Analysis

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 the local branch of Atmospheric Environment Services of Environment 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 the 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 m/s. 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 10 metres per second (m/s). The directional preference and relative magnitude of wind speed changes somewhat from season to season. By convention in microclimate studies, wind direction refers to the wind origin (e.g., a north wind blows from north to south).

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



Notes:

1. Radial distances indicate percentage of time of wind events.
2. Wind speeds represent mean hourly wind speeds measured at 10 m above the ground.

4.4 Pedestrian Comfort Guidelines

Pedestrian comfort guidelines are based on mechanical wind effects without consideration of other meteorological conditions (i.e. temperature, relative humidity). The guidelines provide an assessment of comfort, assuming that pedestrians are appropriately dressed for a specified outdoor activity during any given season. Five pedestrian comfort classes and corresponding gust wind speed ranges are used to assess pedestrian comfort, which include: (i) Sitting; (ii) Standing; (iii) Walking; (iv) Uncomfortable; and (v) Dangerous. More specifically, the comfort classes, associated wind speed ranges, and limiting criteria are summarized as follows:

(i) **Sitting:** Mean wind speeds less than or equal to 10 kilometers per hour (km/h), occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 14 km/h.

(ii) **Standing:** Mean wind speeds less than or equal to 14 km/h, occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 20 km/h.

(iii) **Strolling:** Mean wind speeds less than or equal to 17 km/h, occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 25 km/h.

(iv) **Walking:** Mean wind speeds less than or equal to 20 km/h, occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 30 km/h.

(v) **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 guideline.

(vi) **Dangerous:** Gust equivalent mean wind speeds greater than or equal to 90 km/h, occurring more often than 0.1% of the time, are classified as dangerous. From calculations of stability, it can be shown that gust wind speeds of 90 km/h would be the approximate threshold wind speed that would cause an average elderly person in good health to fall.

Gust speeds are used in the criteria because people 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 cause 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 20% of the time, the activity level would be judged to be uncomfortable by most people. For instance, if wind speeds of 14 km/h were exceeded for more than 20% of the time, most pedestrians would judge that location to be too windy for sitting or more sedentary activities. Similarly, if 30 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 across the study site, 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. 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
Cafés / Patios / Benches / Gardens	Sitting
Transit Shelters	Standing
Public Parks / Plazas	Strolling
Garage / Service Entrances	Walking
Parking Lots	Walking
Vehicular Drop-Off Zones	Walking

5. RESULTS AND DISCUSSION

The following discussion of predicted pedestrian wind conditions for the study site is accompanied by Figures 3A through 6B (following the main text) illustrating the seasonal wind conditions at grade level and on the rooftop exterior amenity spaces. The colour contours indicate predicted regions of the various comfort classes. 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.

Loretta Avenue Sidewalk and Building Entrances (Tag A-D): The sidewalk along Lorretta Avenue (Tag A) will be generally be comfortable for sitting during the summer season, becoming suitable for standing during the three colder seasons. Wind conditions near the northwest corner of Tower 3 (Tag B) will be somewhat windier, and comfortable for standing during the summer, becoming suitable for walking or better during the three colder seasons. The entrances on the west side of Tower 1 (Tag C) and Tower 3 (Tag D) will be comfortable for sitting during the summer season, becoming suitable for standing or better during the three colder seasons. The noted conditions are acceptable for the intended pedestrian uses of the spaces.

Gladstone Avenue Sidewalk, Bus Stops, and Building Entrances (Tag E-H): The sidewalk along Gladstone Avenue (Tag E) will be comfortable for standing during the summer season, becoming suitable for walking or better during the three colder seasons. If the bus stop at the northeast corner of the intersection of Gladstone Avenue and Loretta Avenue (Tag F) will be maintained once the development is complete, it is recommended to install a transit shelter to provide relief from oncoming winds. The bus stop at the southwest corner at the intersection of Lorretta Avenue and Gladstone Avenue (Tag G) will be comfortable for standing throughout the year, which is acceptable. The recessed building entrances at the south side of the site (Tag H) will be comfortable for sitting throughout the year.

Multi-Use Pathway (Tag I): The pathway northeast of the development will be comfortable for standing or better during the summer, becoming comfortable for strolling or better during the three colder seasons. If designated seating areas will be provided in this area, it is recommended to introduce localized wind barriers rising 1.8 metres above the walking surface to shield from northwesterly winds. These wind barriers may take the form of high-solidity architectural wind screens and/or dense coniferous plantings.

North Walkway (Tag J): The walkway along the north side of Tower 3 will be comfortable for standing during the summer, becoming comfortable for walking or better during the three colder seasons. The noted conditions are acceptable for the intended pedestrian uses of the spaces.

Central Courtyard, Driveway, and Building Entrances (Tag K-M): The central courtyard (Tag K) will be comfortable for sitting during the summer, becoming comfortable for standing or better during the three colder seasons. The adjacent driveway areas (Tag L) will experience conditions suitable for standing, or better, throughout the year. The nearby primary building entrances (Tag M) will experience conditions suitable for sitting throughout the year. The noted conditions are acceptable for the intended pedestrian uses of the spaces.

Gladstone Station and Train Platforms (Tags N & O): Wind conditions at the Gladstone Station entrance areas (Tag N) will be comfortable for sitting or more sedentary activities throughout the year. The train platforms (Tag O) will experience conditions comfortable for standing or better throughout the year. The noted conditions are acceptable for the intended pedestrian uses of the spaces.

Grade Level Terrace (Tag P): The grade level amenity terrace located on the east side of the connecting lobby between Towers 2 and 3 will be comfortable for sitting throughout the year without the need for mitigation.

Rooftop Amenity Terraces (Tags Q-S): To ensure that conditions over the 7th floor rooftop terrace (Tag Q) are suitable for sitting during the typical use period of late spring to early autumn, it is recommended to install a wind barrier along the perimeter of the terrace measuring 2.0 metres above the walking surface, combined with localized, 1.8-metre-tall, high-solidity wind barriers immediately upwind of designated seating areas to shield from west-quadrant winds.

To ensure that conditions are suitable for sitting during the typical use period for the 2nd floor rooftop terrace area between Towers 1 and 2 (Tag R), as well as the terrace between Towers 2 and 3 (Tag S), it is recommended to install a perimeter wind barrier measuring 1.8 metres above the walking surface for both spaces.

Influence of the Proposed Development on Existing Wind Conditions near the Study Site: Wind conditions over surrounding sidewalks and beyond the development site will generally be comfortable for standing, or better, during each seasonal period upon introduction of the proposed development, which is acceptable.

Wind Safety: Within the context of typical weather patterns, which exclude anomalous localized storm events such as tornadoes and downbursts, no grade-level areas over the study site were found to experience wind conditions that are considered uncomfortable for walking, or unsafe.

6. SUMMARY AND RECOMMENDATIONS

This document summarizes the results of a pedestrian level wind study undertaken for the proposed mixed-use development at 145 Loretta Avenue and 951 Gladstone Avenue in Ottawa, Ontario. This work is based on industry standard CFD simulation and data analysis procedures, architectural drawings provided by Hobin Architecture Incorporated in September 2018, surrounding street layouts and existing and approved future building massing information obtained from the City of Ottawa, as well as recent site imagery.

Based on CFD test results, interpretation, and experience with similar developments, we conclude the following:

i. The majority of grade-level areas within and surrounding the development site will be acceptable for the intended pedestrian uses on a seasonal basis. More specifically, surrounding sidewalks, exterior amenity areas and building access points will experience acceptable wind conditions throughout the year.

ii. If designated seating areas will be provided along the pathway located northeast of the development, it is recommended to introduce localized wind barriers rising 1.8 metres above the walking surface to shield from northwesterly wind directions.

iii. If the bus stop at the northeast corner of Lorretta Avenue and Gladstone Avenue will be maintained once the proposed building is in place, it is recommended to install a bus shelter to provide relief from oncoming winds.

iv. For the 7th floor terrace over the podium rooftop of Tower 1, it is recommended that 2.0 metre-tall high-solidity wind barriers be installed along the perimeter of the terrace, in addition to localized wind barriers rising 1.8 metres in certain areas designated for seating, to shield from west quadrant winds.

v. For the 2nd floor rooftop terraces between Towers 1 and 2, as well as between Towers 2 and 3, it is recommended that 1.8 metre-tall high-solidity wind barriers be installed along the perimeter of the terraces to ensure conditions will be suitable for sitting or more sedentary activities during the typical use period.

vi. Excluding anomalous localized storm events such as tornadoes and downbursts, no areas over the study site are considered unsafe.

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

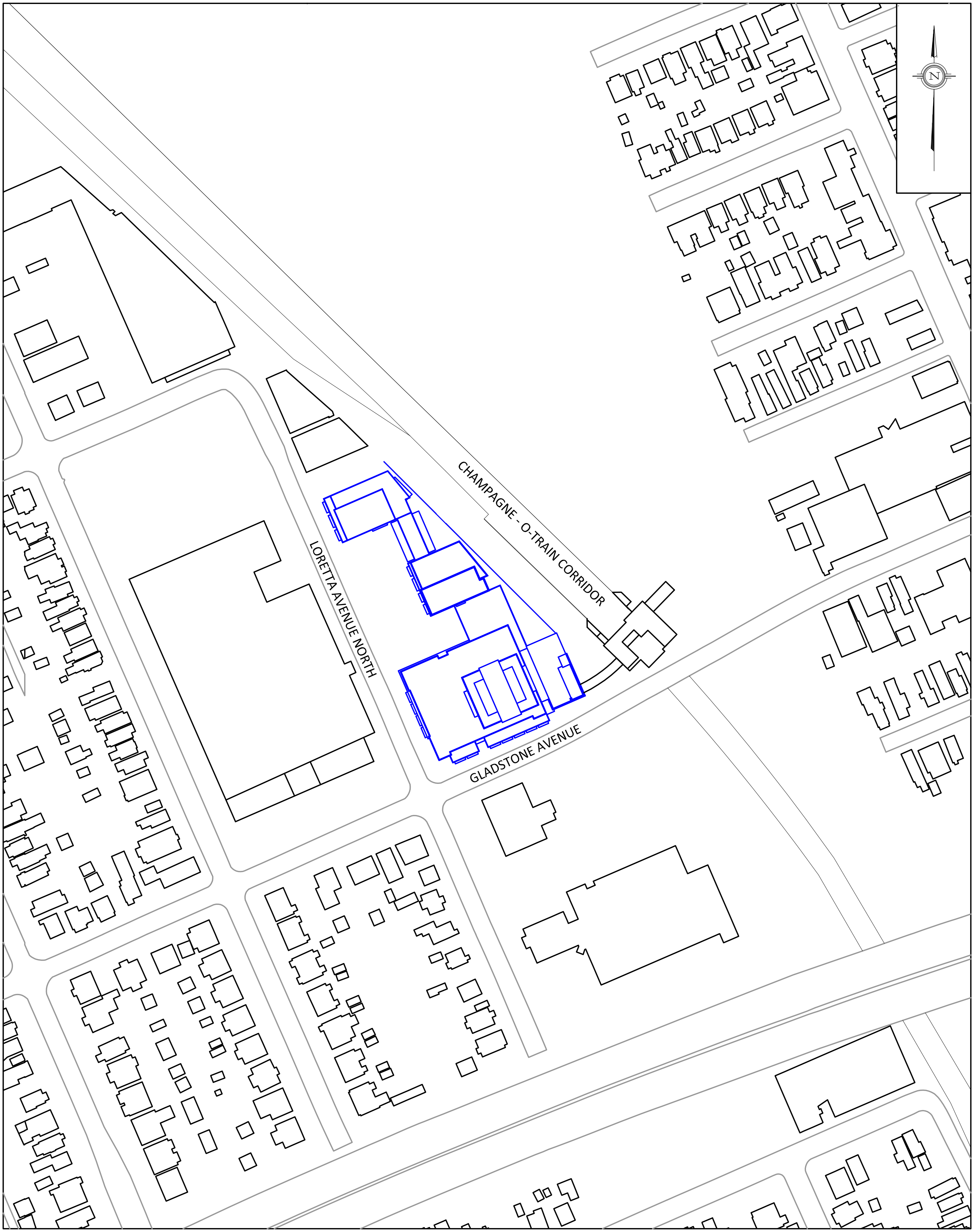
Sincerely,

Gradient Wind Engineering Inc.

Andrew Sliasas, M.A.Sc., P.Eng.
Principal

Edward Urbanski, M.Eng.
Junior Wind Scientist

GWE18-075-CFDPLW



127 Walgreen Road Ottawa, Ontario (613) 836 0934 GRADIENT WIND ENGINEERING INC	PROJECT: 145 LORETTA AVE & 951 GLADSTONE AVE, OTTAWA PEDESTRIAN LEVEL WIND STUDY		DESCRIPTION: FIGURE 1: SITE PLAN AND SURROUNDING CONTEXT
	SCALE: 1:2500 (APPROX.)	DRAWING NO. GWE18-075-CFDPLW-1	
	DATE: OCTOBER 1, 2018	DRAWN BY: B.J.	

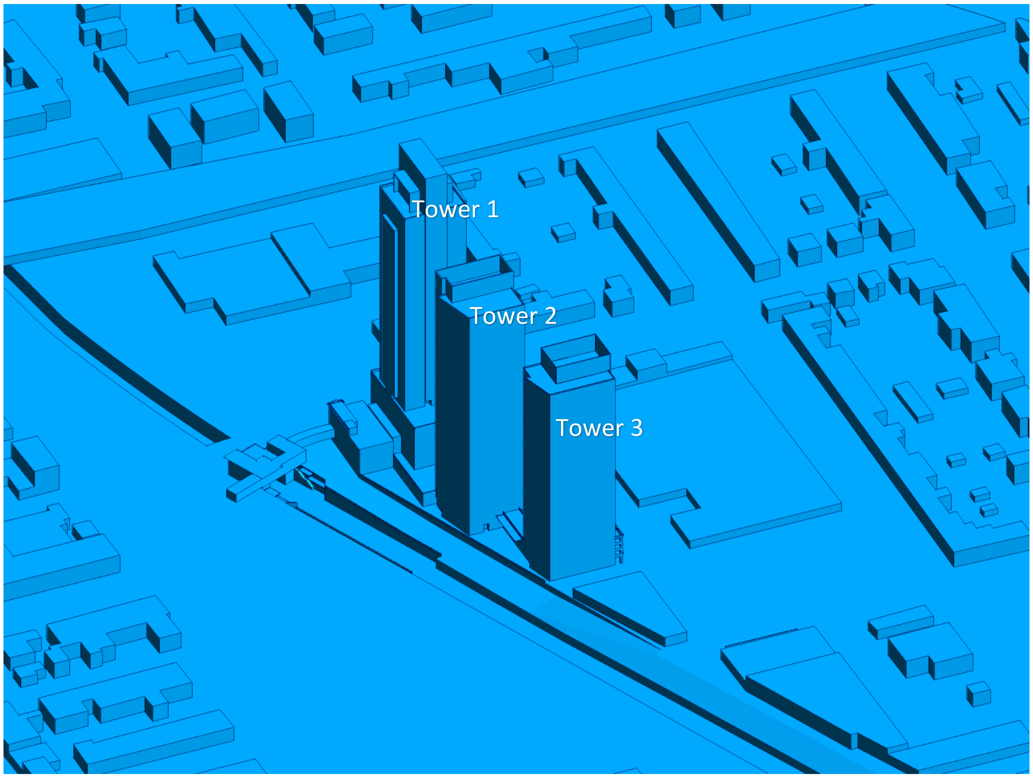


FIGURE 2A: COMPUTATIONAL MODEL, NORTH PERSPECTIVE

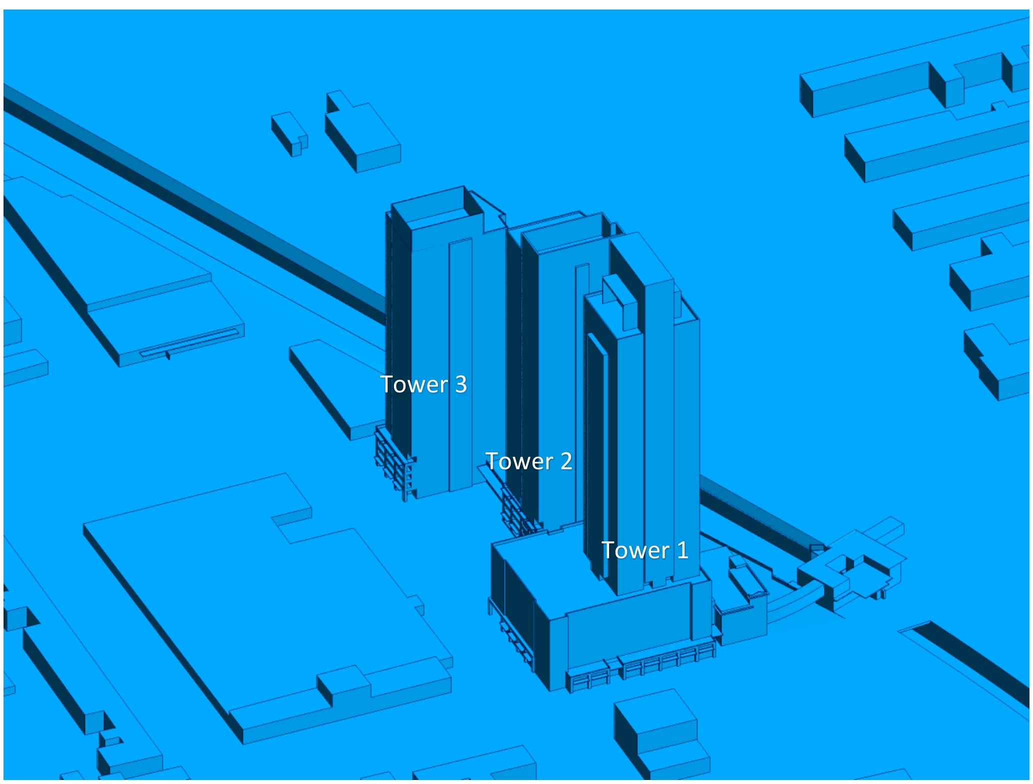
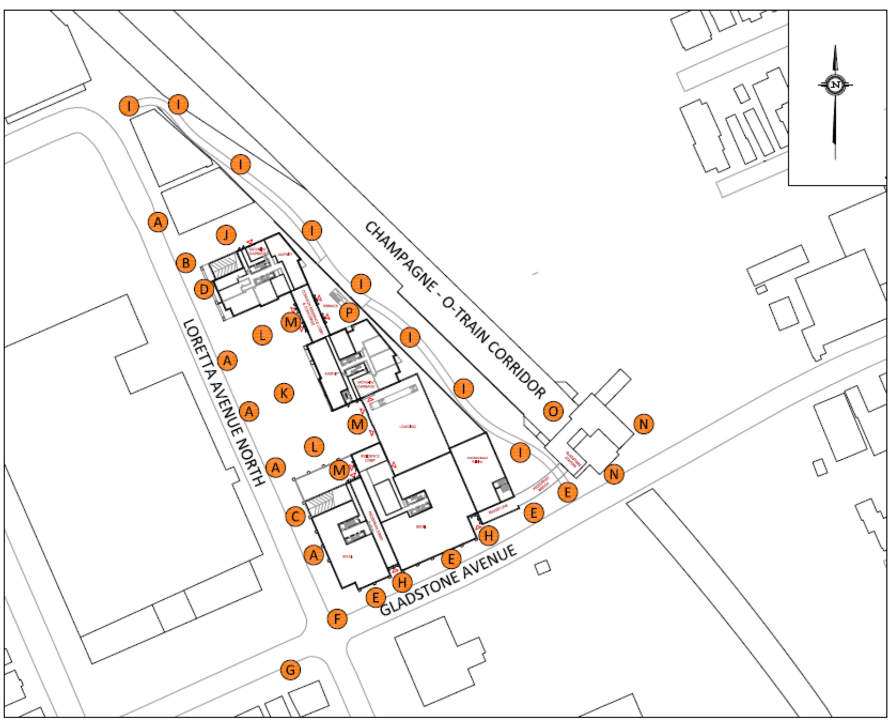


FIGURE 2B: STUDY BUILDINGS, SOUTH PERSPECTIVE

FIGURE 3A: SPRING – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS



GRADE LEVEL REFERENCE MARKER LOCATIONS

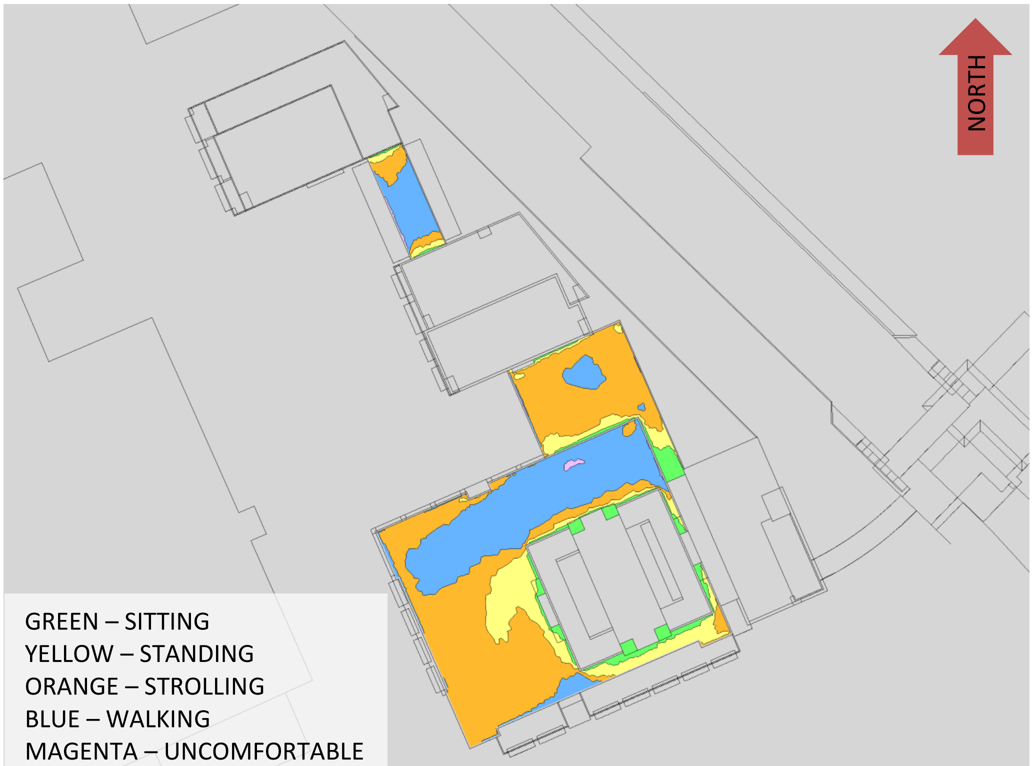
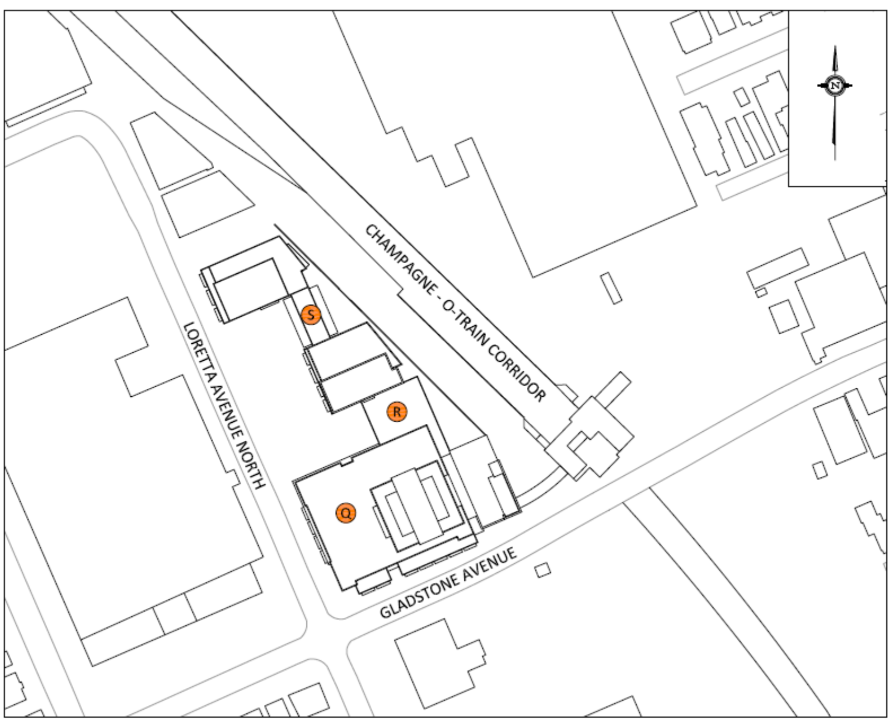


FIGURE 3B: SPRING – PODIUM ROOFTOP TERRACE WIND CONDITIONS



ELEVATED OUTDOOR AMENITY AREA REFERENCE MARKER LOCATIONS

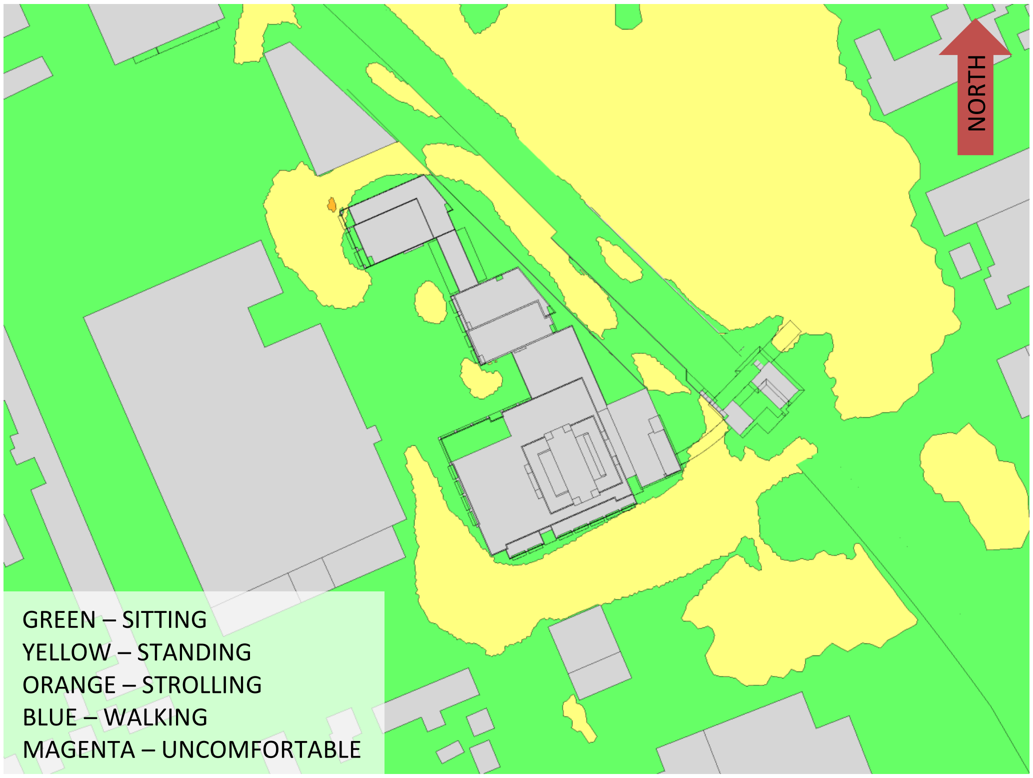
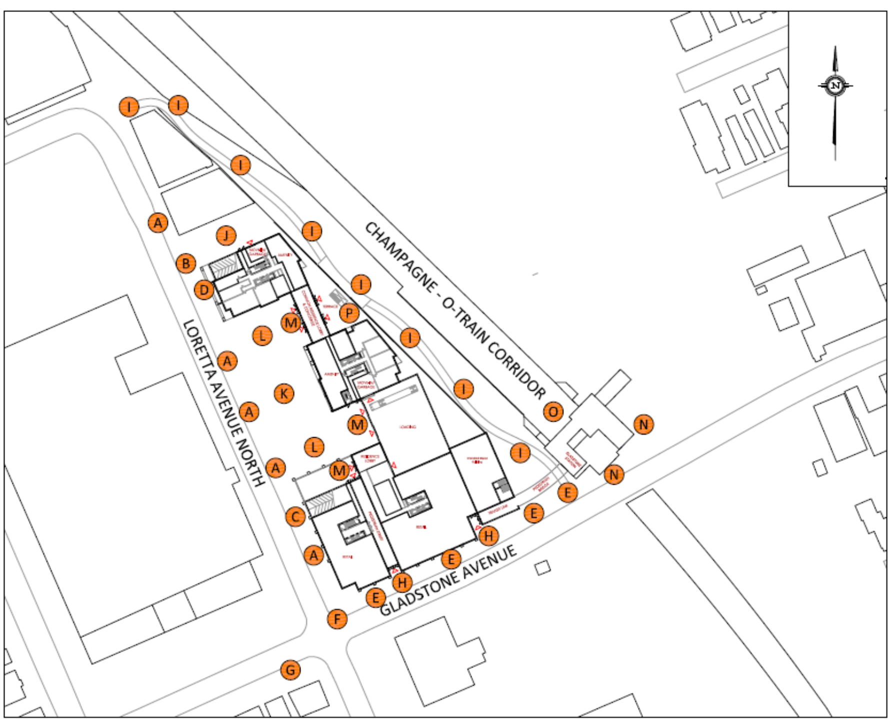


FIGURE 4A: SUMMER – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS



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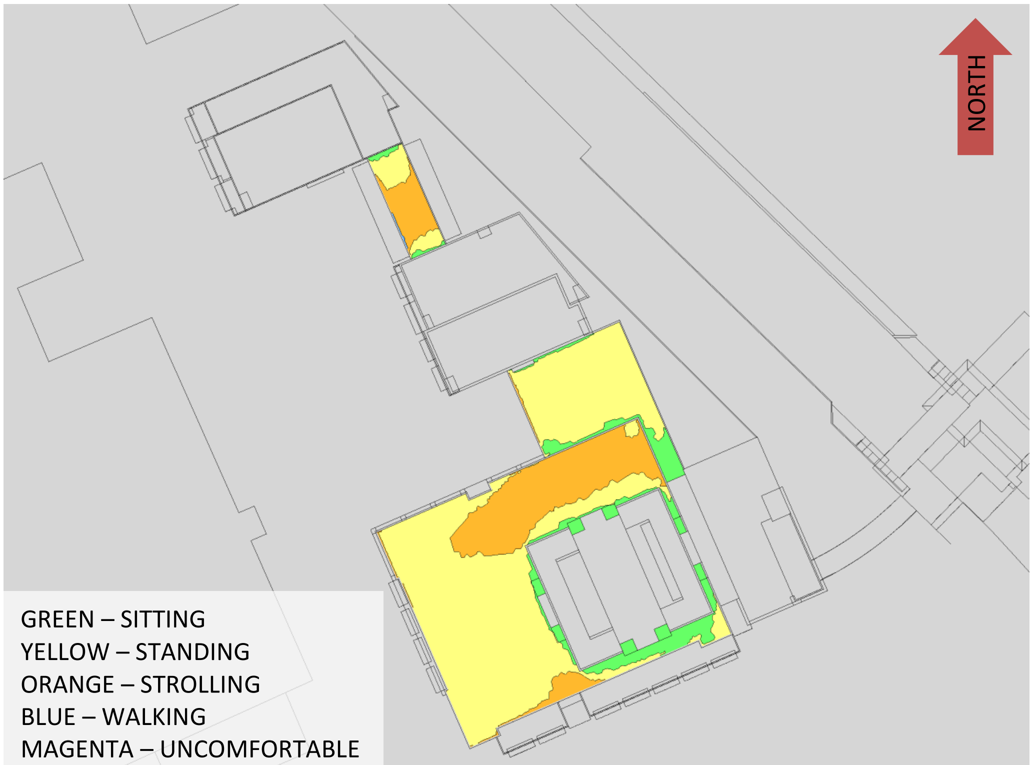
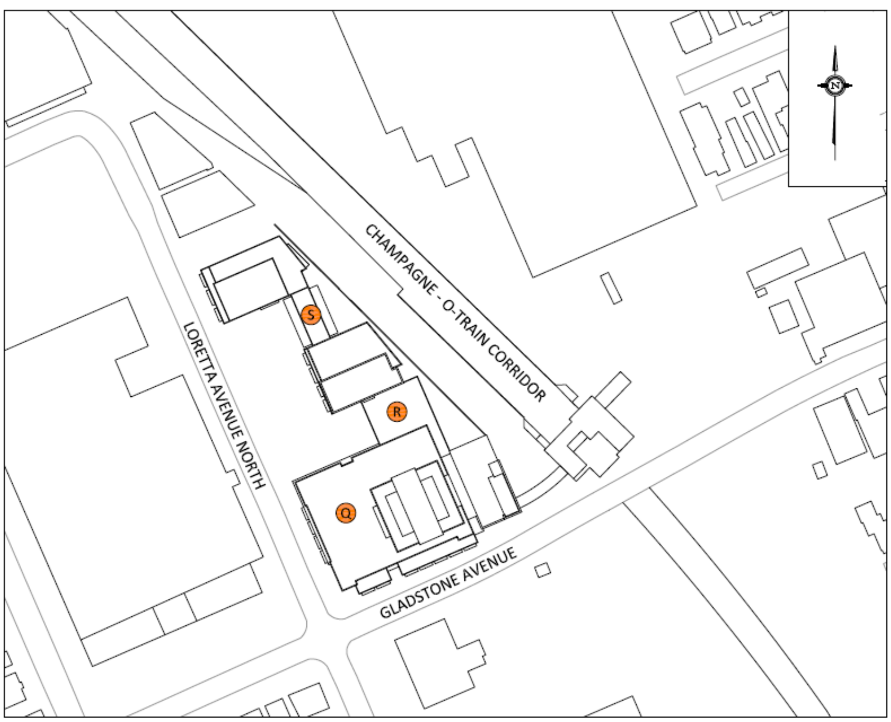
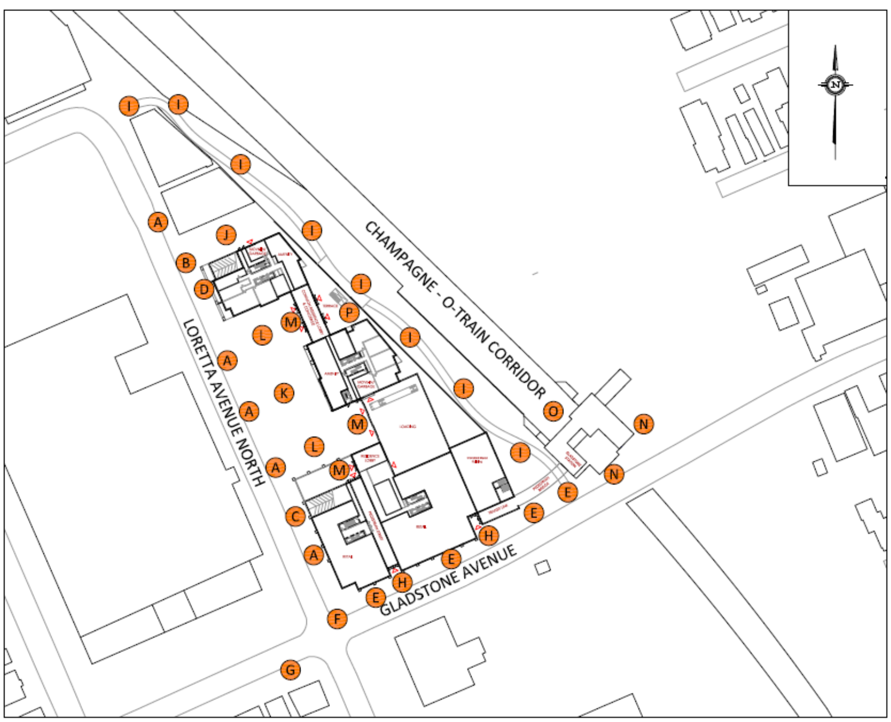


FIGURE 4A: SUMMER – PODIUM ROOFTOP TERRACE WIND CONDITIONS



ELEVATED OUTDOOR AMENITY AREA REFERENCE MARKER LOCATIONS

FIGURE 5A: AUTUMN – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS



GRADE LEVEL REFERENCE MARKER LOCATIONS

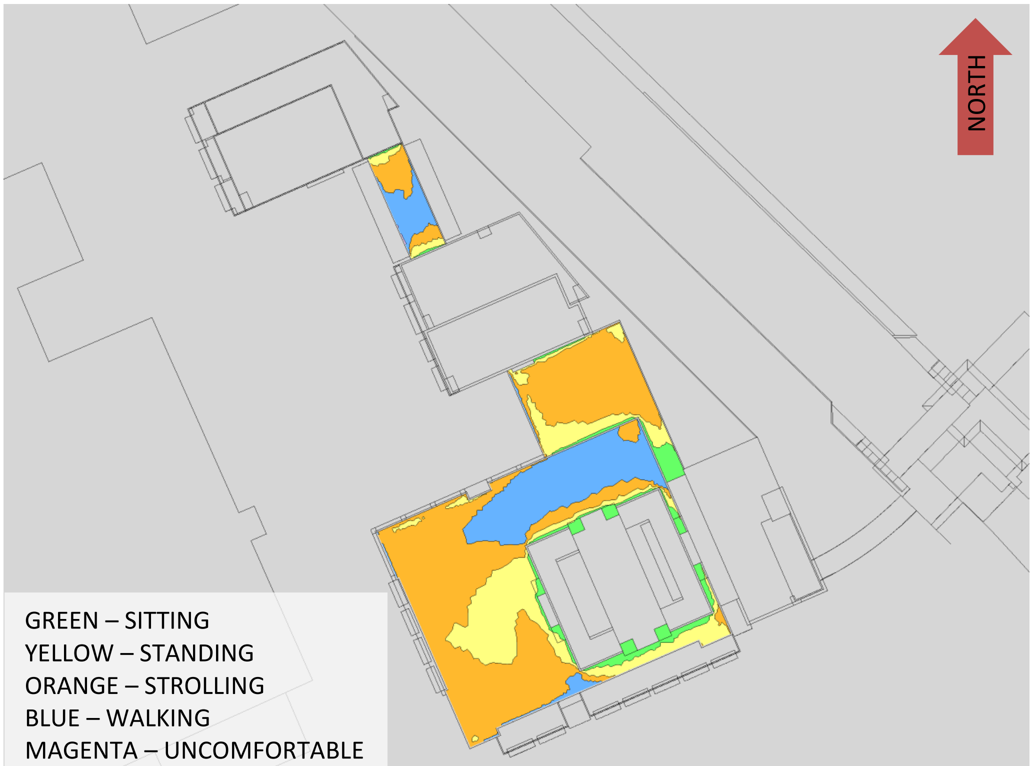
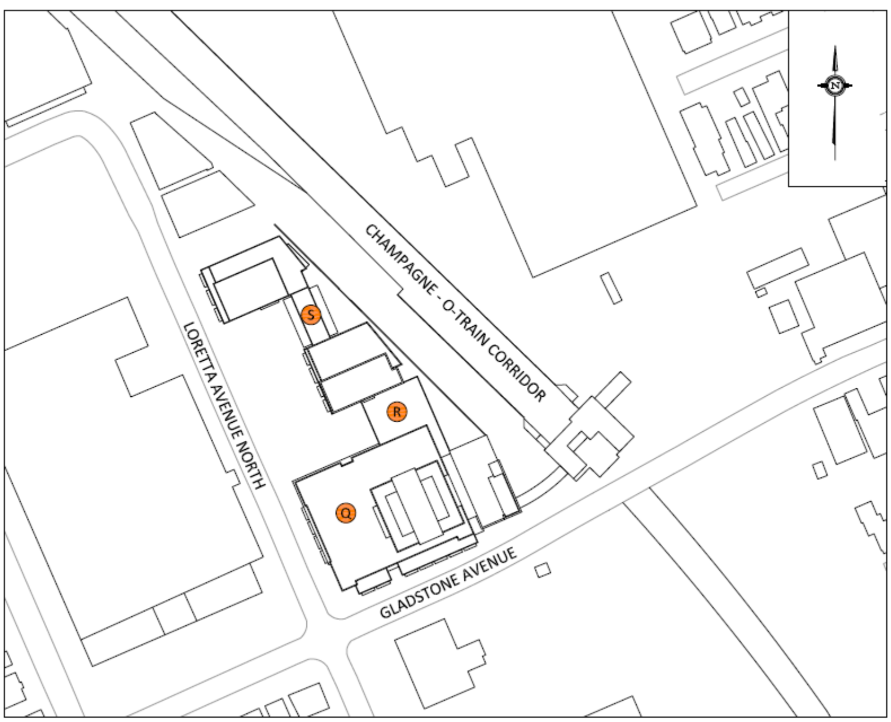


FIGURE 5B: AUTUMN – PODIUM ROOFTOP TERRACE WIND CONDITIONS



ELEVATED OUTDOOR AMENITY AREA REFERENCE MARKER LOCATIONS

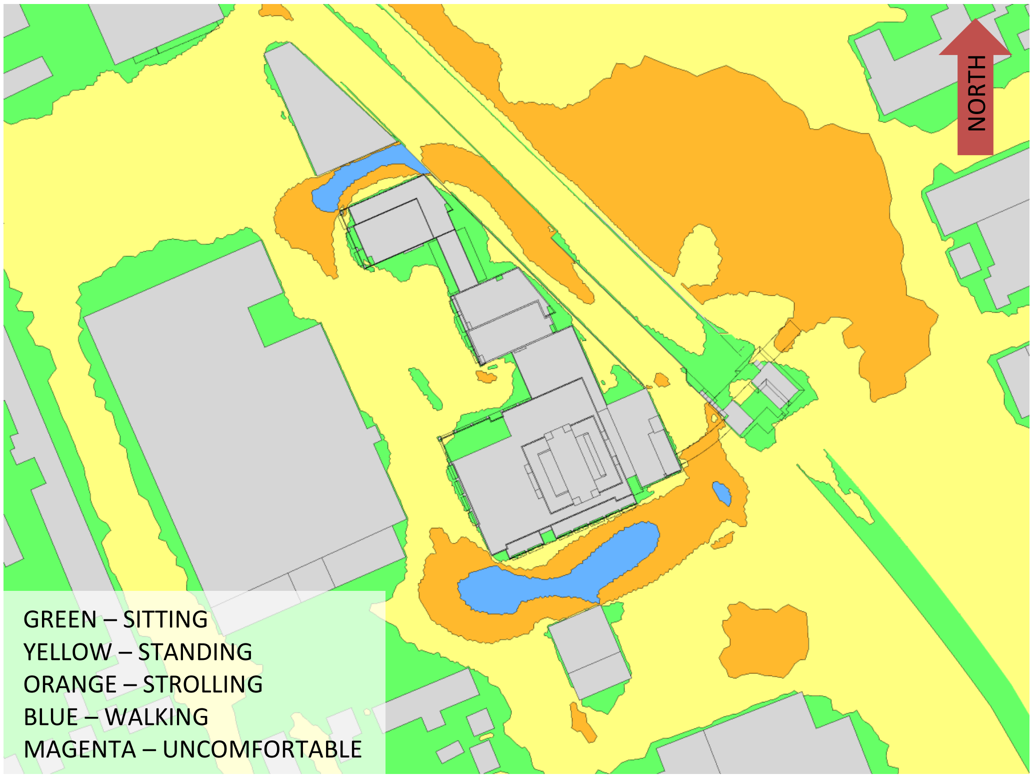
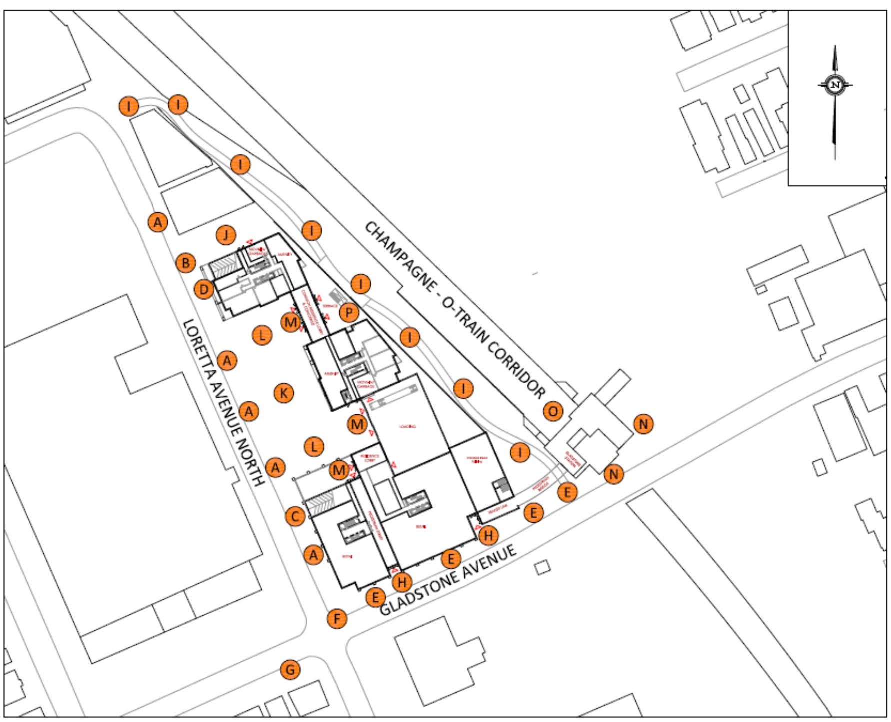


FIGURE 6A: WINTER – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS



GRADE LEVEL REFERENCE MARKER LOCATIONS

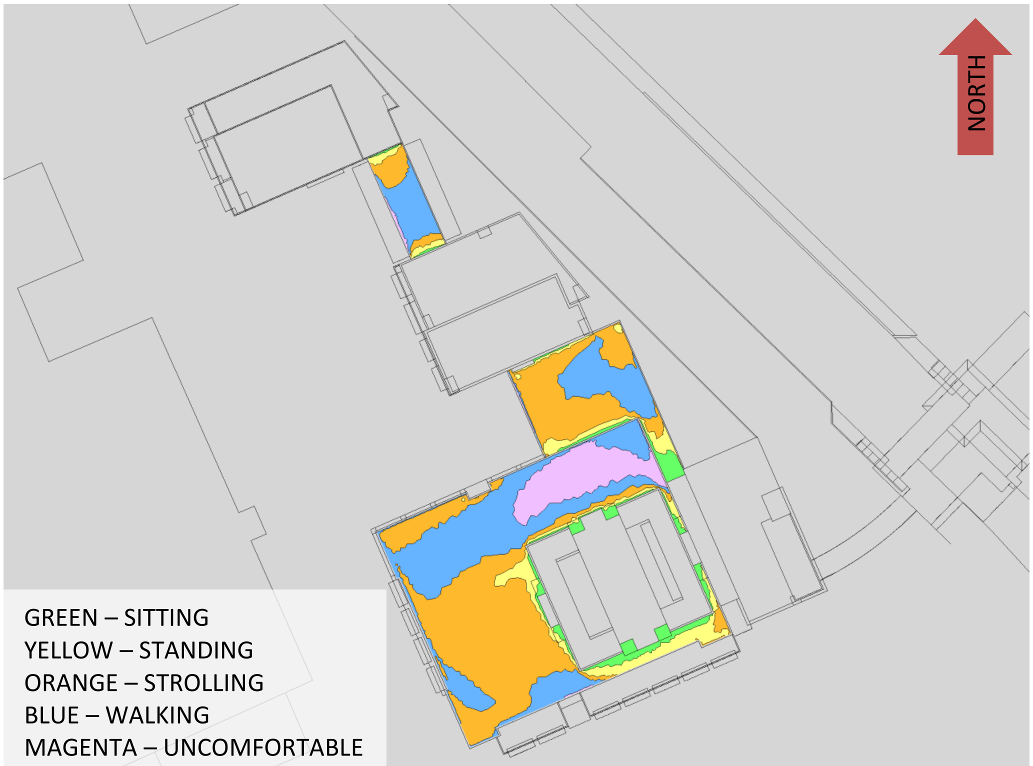
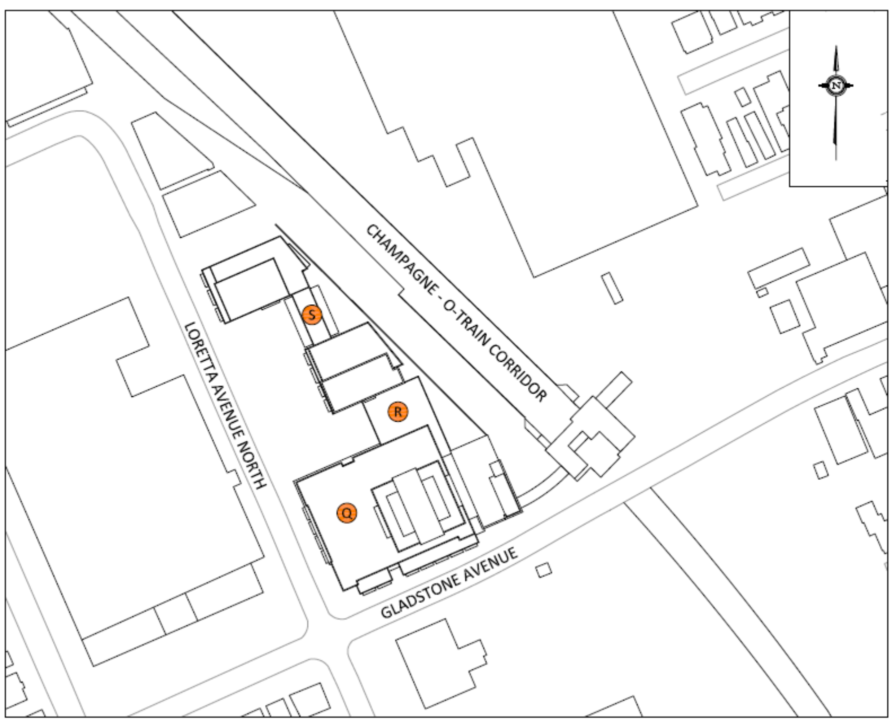


FIGURE 6B: WINTER – PODIUM ROOFTOP TERRACE WIND CONDITIONS



ELEVATED OUTDOOR AMENITY AREA REFERENCE MARKER LOCATIONS

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

WIND TUNNEL 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 m to 600 m.

Simulating real wind behaviour in a wind tunnel, or by computer models (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, U_g = gradient wind speed, ***Z*** = height above ground, Z_g = depth of the boundary layer (gradient height) and α is the power law exponent.

Figure A1 plots three such profiles for the open country, suburban and urban exposures. The exponent α varies according to the type of terrain; α = 0.14, 0.25 and 0.33 for open country, suburban and urban exposures respectively. Figure A2 illustrates the theoretical variation of turbulence in full scale and some wind tunnel measurement for comparison.

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. For a 1:300 scale, for example, 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***, ***U_{10}*** 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 center 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.

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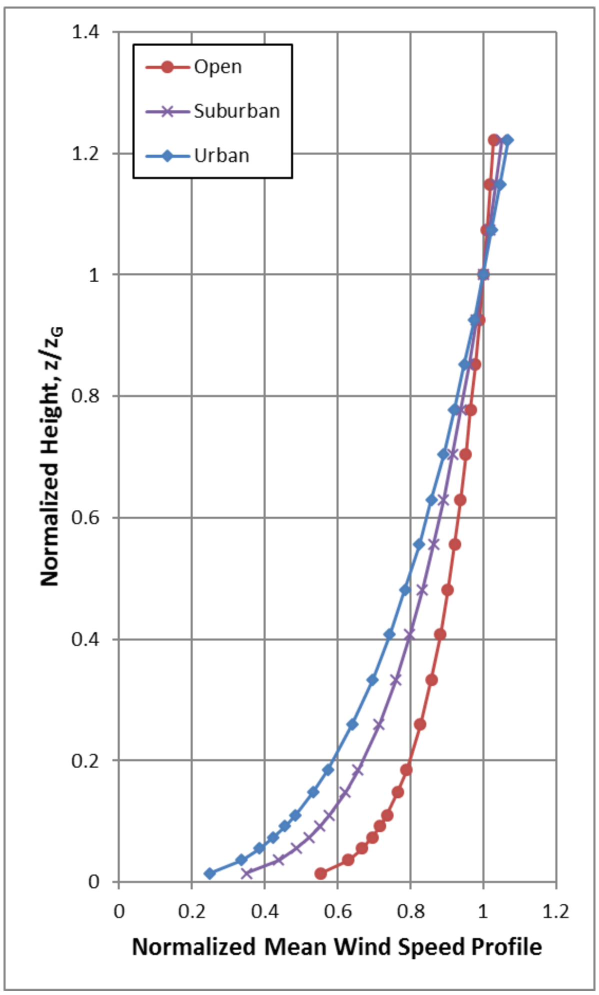


Figure A1: Mean Wind Speed Profiles

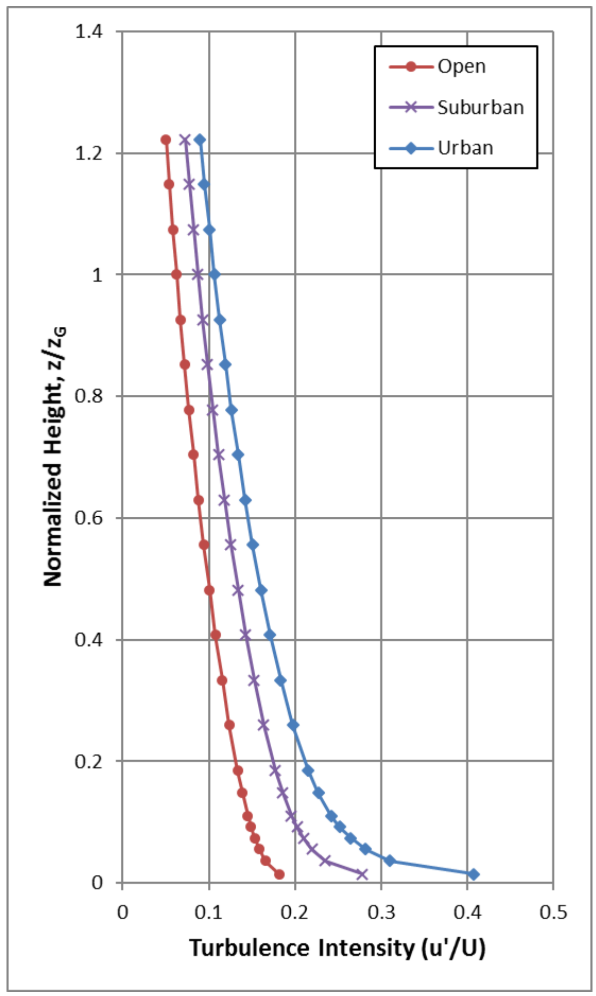


Figure A2: Turbulence Intensity Profiles

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

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 B. 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:

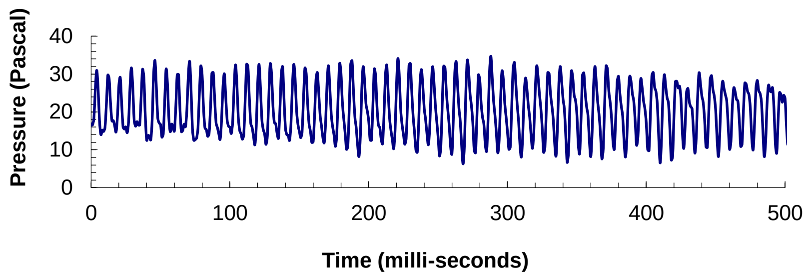
$$P_N(>20) = \Sigma_\theta P\left[\frac{(>20)}{\left(\frac{U_N}{U_g}\right)}\right]$$

$$P_N\ (>20) = \Sigma_\theta\, P\ \{>20/(U_N/Ug)\}$$

Where, U_N/U_g is the aforementioned normalized 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 B: TIME VERSUS VELOCITY TRACE FOR A TYPICAL WIND SENSOR



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