# Pedestrian Level Wind Study

## 409 Brant Street

## Burlington, Ontario

REPORT: GWE17-195-CFDPLW

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December 21, 2017

# EXECUTIVE SUMMARY

This report describes a detailed pedestrian level wind study for the proposed mixed-use residential development located at 409 Brant Street in Burlington, Ontario. The study involves simulation of wind speeds for selected wind directions in a three-dimensional 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.

The study was performed in accordance with the scope of work described in GWE proposal #17-298P, dated November 24, 2017, and is based on industry-standard CFD simulation and data analysis procedures, architectural drawings provided by Graziani + Corazza Architects Inc. in December 2017, surrounding street layouts and existing and approved future building massing information obtained from the City of Burlington, 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, as well as in Figures 3A-6B (following the main text). Based on CFD test results, interpretation, and experience with similar developments, all areas at grade within and surrounding the development site will be acceptable for the intended pedestrian uses on a seasonal basis. More specifically, surrounding sidewalks, building access points, the nearby transit stop and restaurant patio, as well as the Burlington City Hall civic plaza will experience calm and acceptable wind conditions throughout the year. Additionally, the Level 2 exterior amenity terrace will experience conditions comfortable for sitting, or more sedentary activities throughout the year.

Regarding the upper rooftop amenity terrace, the majority of the area will experience conditions comfortable for sitting during the summer season. The western portion of the terrace will generally be comfortable for standing during the summer season, becoming suitable for walking during the remaining colder seasons. Additionally, small regions of the western portion of the terrace are also predicted to become uncomfortable and occasionally hazardous during the three colder seasons. Therefore, to increase comfort during the typical use period and safety throughout the year, we recommend providing 1.8-metre (m) tall wind barriers in place of standard guards along the west perimeter of the terrace, continuing 8 m along both the north and south perimeters of the area.

Excluding anomalous localized storm events such as tornadoes and downbursts, no areas over the study site at grade level were found to be uncomfortable or unsafe.

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# 1. INTRODUCTION

Gradient Wind Engineering Inc. (GWE) was retained by Reserve Properties Ltd. to undertake a detailed Pedestrian Level Wind (PLW) study for the proposed mixed-use residential development located at 409 Brant Street in Burlington, Ontario. Our mandate within this study, as outlined in GWE proposal #17-298P, dated November 24, 2017, 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 computer simulations using the Computational Fluid Dynamics (CFD) technique and data analysis procedures, architectural drawings provided by Graziani + Corazza Architects Inc. in December 2017, surrounding street layouts and existing and approved future building massing information obtained from the City of Burlington, as well as recent site imagery.

# 2. TERMS OF REFERENCE

The focus of this PLW study is the proposed mixed-use residential development located at 409 Brant Street in Burlington, Ontario. The subject site is located on a parcel of land bounded by Brant Street to the southwest, James Street to the northwest, John Street to the northeast, and an existing grade-level parking lot to the southeast. For ease of description, James Street is defined as project north. The site is also located to the north of Burlington City Hall.

The near-field surroundings are characterized by a suburban mix of low- and medium-rise residential developments in all directions, with the exception of several taller buildings along Lakeshore Road to the southeast and Maria Street to the north. Also, the approved 23-storey building at 421 Brant Street is situated to the north of the study site. At greater distances from the study site, the exposures can be generally characterized by a suburban mix of low- and medium-rise developments to the south rotating clockwise to the east, with the exception of a series of high-rise towers along Lakeshore Road and Maple Avenue. To the southeast, this suburban mix gives way to Lake Ontario, which is approximately 400 metres (m) to the southeast of the study site.

The proposed development features a 23-storey building rising above a 4-storey podium. Upon completion, the development will reach a total height of approximately 80 m when measured from grade to the top of the mechanical penthouse. The podium features a generally rectangular floorplate with a 2-storey cut-out at the northwest corner and incorporates the façade of two existing buildings at the southeast and southwest corners of the site. Above five levels of below grade parking, the ground floor includes a retail space that extends along the James Street elevation and partially along the John Street elevation. A second retail space occupies the southwest corner of the ground floor. The residential lobby is accessible from the centre of the Brant Street elevation. Access to below-grade parking, as well as a loading area, is provided near the south end of the John Street elevation. At Level 2 the floorplate steps-back on the east, south and west elevations, providing areas for private balconies and an outdoor amenity terrace along the centre of the south elevation. At Level 3 the floorplate steps-back on the south elevation, providing space for private balconies. At Level 5 the floorplate steps-back on all elevations, after which the building rises uniformly to the roof. The building also features a rooftop outdoor amenity terrace at the mechanical penthouse level.

Key areas under consideration for pedestrian wind comfort include: surrounding sidewalks, building access points, and the elevated outdoor amenity areas at Level 2 and the upper rooftop. Figure 1A illustrates the study site and surrounding context, while Figure 1B illustrates the noted outdoor amenity terraces. 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 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 Computational Fluid Dynamics (CFD) simulations of wind speeds across the study site within a virtual environment, meteorological analysis of the Burlington area wind climate, and synthesis of computational data with industry-accepted guidelines. The following sections describe the analysis procedures, including a discussion of the pedestrian comfort and safety guidelines.

## 4.1 Computer-Based Context Modelling

A computer-based PLW study is performed to determine the influence of local winds at the pedestrian level for a proposed development. The computational model of the proposed development and relevant surroundings, illustrated in 2A and 2B following the main text. The model includes all existing buildings and approved future developments within a full-scale diameter of approximately 840 m. 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 building, complete with surrounding massing within a diameter of approximately 840 metres.

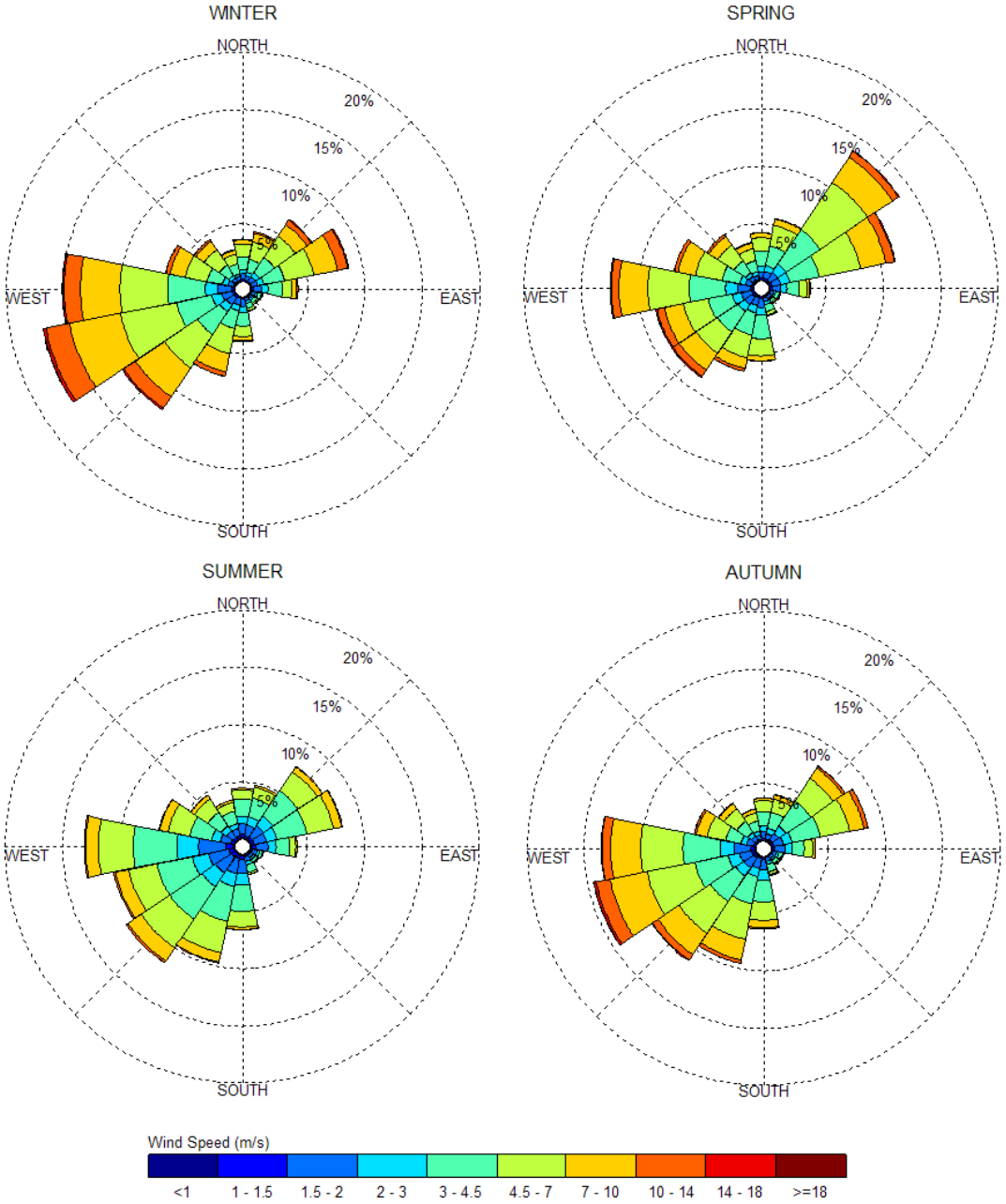
Mean and peak wind speed data obtained over the study site for each wind direction were interpolated to 36 wind directions at 10° intervals, representing the full compass azimuth. Measured wind speeds approximately 1.5 m above local grade, as well as 1.5 m above the outdoor amenity areas, were referenced 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 Burlington was developed from approximately 40-years of hourly meteorological wind data recorded at John C. Munro Hamilton 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 Burlington 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 meters per second (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 Burlington, the most common winds concerning pedestrian comfort occur from the southwest clockwise to the west, as well as those from the northeast. The directional preference and relative magnitude of the wind speed varies somewhat from season to season, with the summer months displaying the calmest winds relative to the remaining seasonal periods.

## SEASONAL DISTRIBUTION OF WINDS FOR VARIOUS PROBABILITIES
## JOHN C. MUNRO HAMILTON INTERNATIONAL AIRPORT, HAMILTON, ONTARIO




**Notes:**

1. Radial distances indicate percentage of time of wind events.
2. Wind speeds are mean hourly measured at 10 m above the ground.
3. Wind speeds can be converted to km/h by multiplying m/s by a factor of 3.6.

## 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 guidelines are summarized as follows:

(i) **Sitting** – Wind speeds up to 14 km/h occurring at least 70% of the time would be considered acceptable for sedentary activities, including sitting.

(ii) **Standing** – Wind speeds up to 22 km/h occurring at least 80% of the time are acceptable for activities such as standing, strolling or more vigorous activities.

(iii) **Walking** – Wind speeds up to 30 km/h occurring at least 80% of the time are acceptable for walking or more vigorous activities.

(iv) **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 target.

(v) **Dangerous** – Wind speeds greater than 90 km/h, occurring more 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.

The wind speeds associated with the above categories are gust wind speeds. Corresponding mean wind speeds are approximately calculated as gust wind speed divided by 1.5. Gust speeds are used in the guidelines 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 gust speed ranges 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.

**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 70% or 80% 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 30% of the time, most pedestrians would judge that location to be too windy for sitting. 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 guidelines 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 |
|---|---|
| Primary Building Access Point | Standing |
| Secondary Building Access Point | Standing / Walking |
| Public Sidewalks / Pedestrian Walkways | Walking |
| Transit Stops | Sitting / Standing |
| Outdoor Amenity Spaces | Sitting / Standing |
| Cafés / Patios / Benches / Gardens | Sitting / Standing |
| Public Parks | Sitting / Walking |
| Garage / Service Entrances | Walking |
| Vehicular Drop-Off Areas | Standing / Walking |

## 5. RESULTS AND DISCUSSION

The foregoing 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. The colour contours indicate predicted regions of the various comfort classes. Wind conditions comfortable for sitting are represented by the colour green, standing by yellow, and walking by blue. Areas that are considered uncomfortable for walking are represented by the colour magenta.

**Brant Street Sidewalk and Associated Building Access Points (Tags A-D, Figures 3A-6A):** The sidewalk along the west side of the site (Tag A) will generally be comfortable for sitting during the summer season, becoming suitable for standing during the spring and autumn seasons, and walking during the winter season. Towards the southwest corner of the building conditions are somewhat windier and suitable for standing during the summer season, becoming suitable for walking during the remaining colder seasons. Closer to the building, including the two retail entrances (Tags B and D), conditions are somewhat calmer and comfortable for standing, or better, throughout the year, while the main residential lobby entrance (Tag C) will be comfortable for sitting throughout the year. The noted conditions are acceptable for the intended pedestrian uses of the spaces.

**James Street Sidewalk (Tag E, Figures 3A-6A):** The sidewalk along the north side of the site will be comfortable for standing, or better, during the summer season, becoming suitable for walking, or better, during the remaining seasons, which is acceptable.

**John Street Sidewalk and Associated Building Access Points (Tags F and G, Figures 3A-6A):** The sidewalk along the east side of the site (Tag F) will generally be comfortable for sitting during the summer and autumn seasons, becoming suitable for standing during the winter and spring seasons. Towards the south corner of the building, conditions are somewhat windier and suitable for standing during the summer season and walking during the remaining seasons. Closer to the building, including the loading area and the entrance to below-grade parking (Tag G), conditions are calmer and comfortable for sitting throughout the year. The noted conditions are acceptable for the intended pedestrian uses of the spaces.

If retail entrances fronting onto John Street are being considered, wind conditions will be acceptable without mitigation.

**Level 2 Exterior Amenity Terrace (Tag H, Figures 4B-7B):** The Level 2 exterior amenity terrace will be comfortable for sitting, or more sedentary activities, throughout the year, which is acceptable.

**Rooftop Outdoor Amenity Terrace (Tags I-K, Figures 4B-7B):** The south and east areas of the outdoor amenity terrace (Tags J and K) will be comfortable for sitting during the summer season, becoming suitable for standing during the remaining colder seasons. However, conditions within the northeast and southeast corners of roof are somewhat windier and suitable for walking throughout the year. The west portion of the terrace (Tag I) will generally be comfortable for standing during the summer season, becoming suitable for walking during the remaining seasons. Small regions of the west area are also predicted to be uncomfortable and occasionally hazardous during the three colder seasons. Therefore, to increase comfort conditions during the typical use period and ensure safe conditions throughout the year, we recommend providing 1.8-metre (m) tall wind barriers in place of standard guards along the west perimeter of the terrace, continuing 8 m along both the north and south perimeters of the area.

**Influence of the Proposed Development on Existing Wind Conditions near the Study Site:** Wind conditions over surrounding sidewalks beyond the development site, as well as at nearby building entrances, will be comfortable for their intended pedestrian uses during each seasonal period upon the introduction of the proposed development at 409 Brant Street. Furthermore, both the Burlington City Hall civic plaza and The Queen's Head restaurant patio at 400 Brant Street will experience conditions comfortable for sitting, or more sedentary activities, throughout the year. Additionally, the existing transit stop along the west side of John Street, which is situated to the south of the study site, will also experience conditions comfortable for sitting throughout the year.

**Wind Safety:** Within the context of typical weather patterns, which exclude anomalous localized storm events such as tornadoes and downbursts, no areas over the study site, except as noted along the west side of the rooftop outdoor amenity terrace, were found to experience wind conditions that are considered uncomfortable or unsafe.

## 6. SUMMARY AND RECOMMENDATIONS

This document summarizes the results of a pedestrian level wind study for the proposed mixed-use residential development located 409 Brant Street in Burlington, Ontario. The study was performed in accordance with the scope of work described in GWE proposal #17-298P, dated November 24, 2017, and is based on industry-standard CFD simulation and data analysis procedures, architectural drawings provided by Graziani + Corazza Architects Inc. in December 2017, surrounding street layouts and existing and approved future building massing information obtained from the City of Burlington, 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, as well as in Figures 3A-6B (following the main text). Based on CFD test results, interpretation, and experience with similar developments, all areas at grade within and surrounding the development site will be acceptable for the intended pedestrian uses on a seasonal basis. More specifically, surrounding sidewalks, building access points, the nearby transit stop and restaurant patio, as well as the Burlington City Hall civic plaza will experience calm and acceptable wind conditions throughout the year. Additionally, the Level 2 exterior amenity terrace will experience conditions comfortable for sitting, or more sedentary activities throughout the year.

Regarding the upper rooftop amenity terrace, the majority of the area will experience conditions comfortable for sitting during the summer season. The western portion of the terrace will generally be comfortable for standing during the summer season, becoming suitable for walking during the remaining colder seasons. Additionally, small regions of the western portion of the terrace are also predicted to become uncomfortable and occasionally hazardous during the three colder seasons. Therefore, to increase comfort conditions during the typical use period and ensure safe conditions throughout the year, we recommend providing 1.8-m tall wind barriers in place of standard guards along the west perimeter of the terrace, continuing 8 m along both the north and south perimeters of the area.

Excluding anomalous localized storm events such as tornadoes and downbursts, no areas over the study site at grade level are considered uncomfortable or unsafe

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

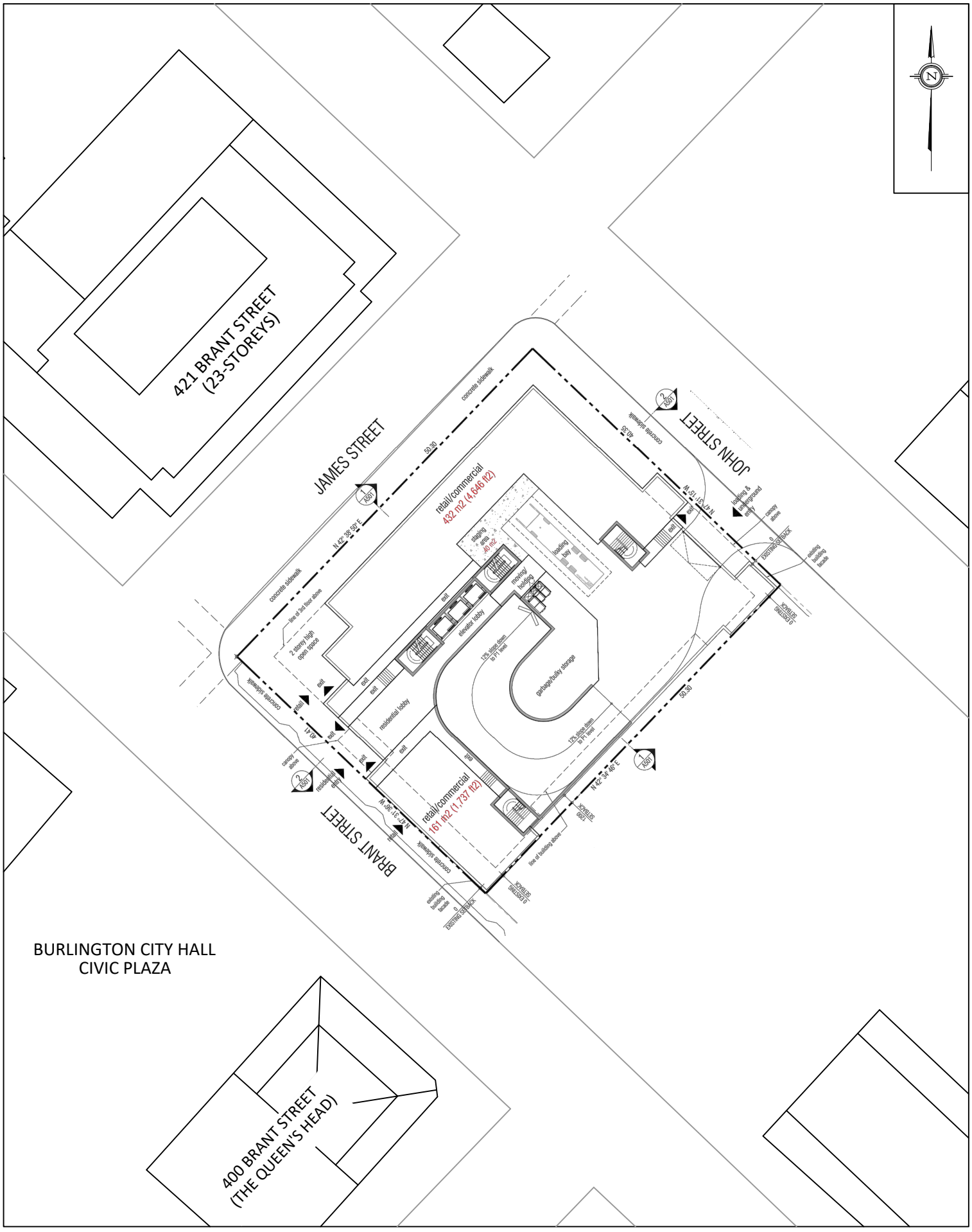
Sincerely,

***Gradient Wind Engineering Inc.***


Nicolas Pratt, M.E.Sc.
Junior Wind Scientist

Vincent Ferraro, M.Eng., P.Eng.
Managing Principal

Justin Ferraro
Principal





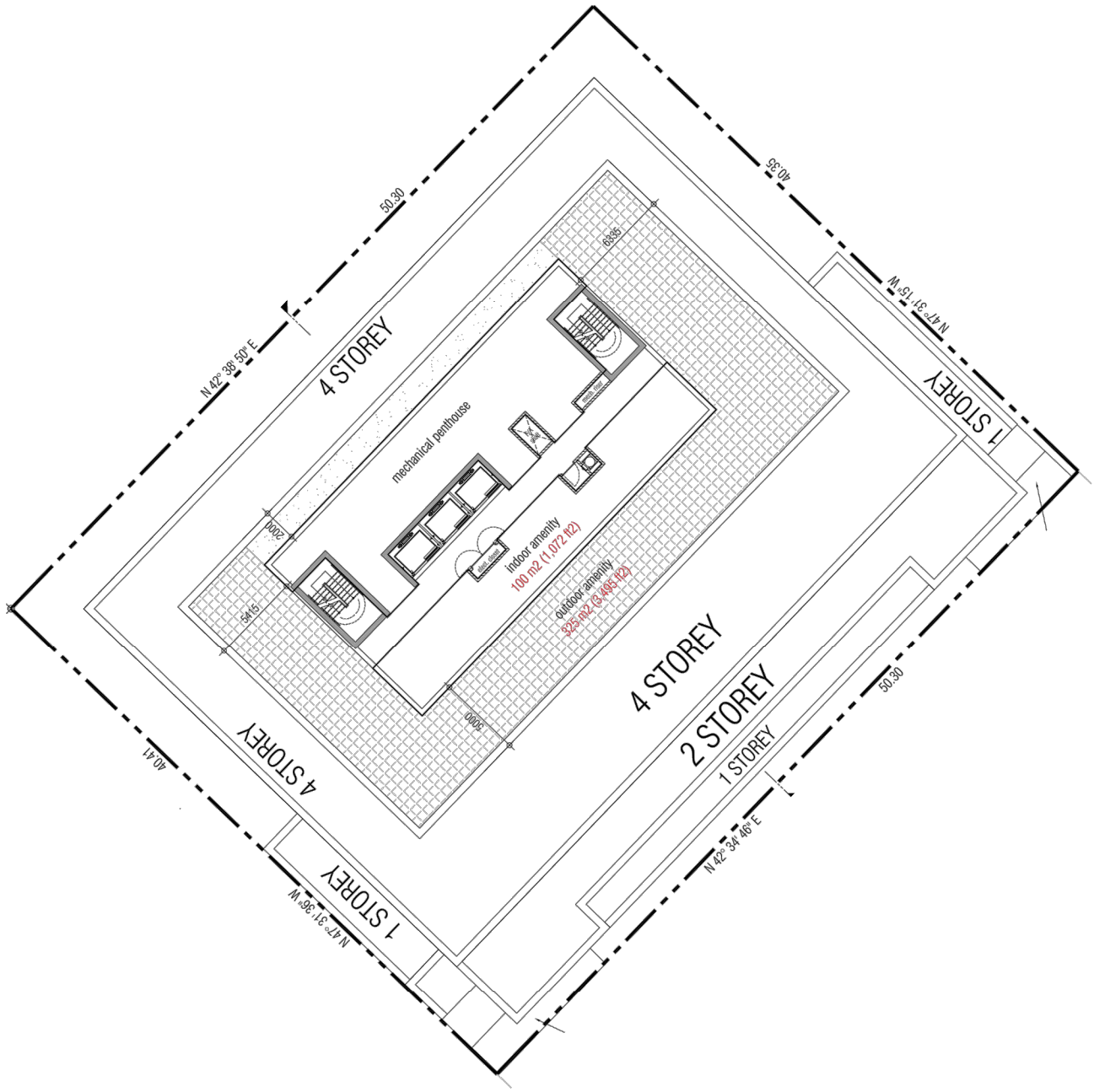
GRADIENT WIND ENGINEERING INC

127 Walgreen Road
Ottawa, Ontario
(613) 836 0934


| | |
|---|---|
| PROJECT | 409 BRANT STREET, BURLINGTON<br>PEDESTRIAN LEVEL WIND STUDY |
| SCALE | 1:600 (APPROX.) |
| DRAWING NO. | GWE17-195-PLW-1A |
| DATE | DECEMBER 21, 2017 |
| DRAWN BY | K.A. |

DESCRIPTION

FIGURE 1A:
SITE PLAN AND SURROUNDING CONTEXT




127 Walgreen Road
Ottawa, Ontario
(613) 836 0934

GRADIENT WIND ENGINEERING INC

| | |
|---|---|
| PROJECT | 409 BRANT STREET, BURLINGTON<br>PEDESTRIAN LEVEL WIND STUDY |
| SCALE | 1:400 (APPROX.) |
| DRAWING NO. | GWE17-195-PLW-1B |
| DATE | DECEMBER 21, 2017 |
| DRAWN BY | K.A. |

DESCRIPTION

FIGURE 1B:
ELEVATED OUTDOOR AMENITY AREAS

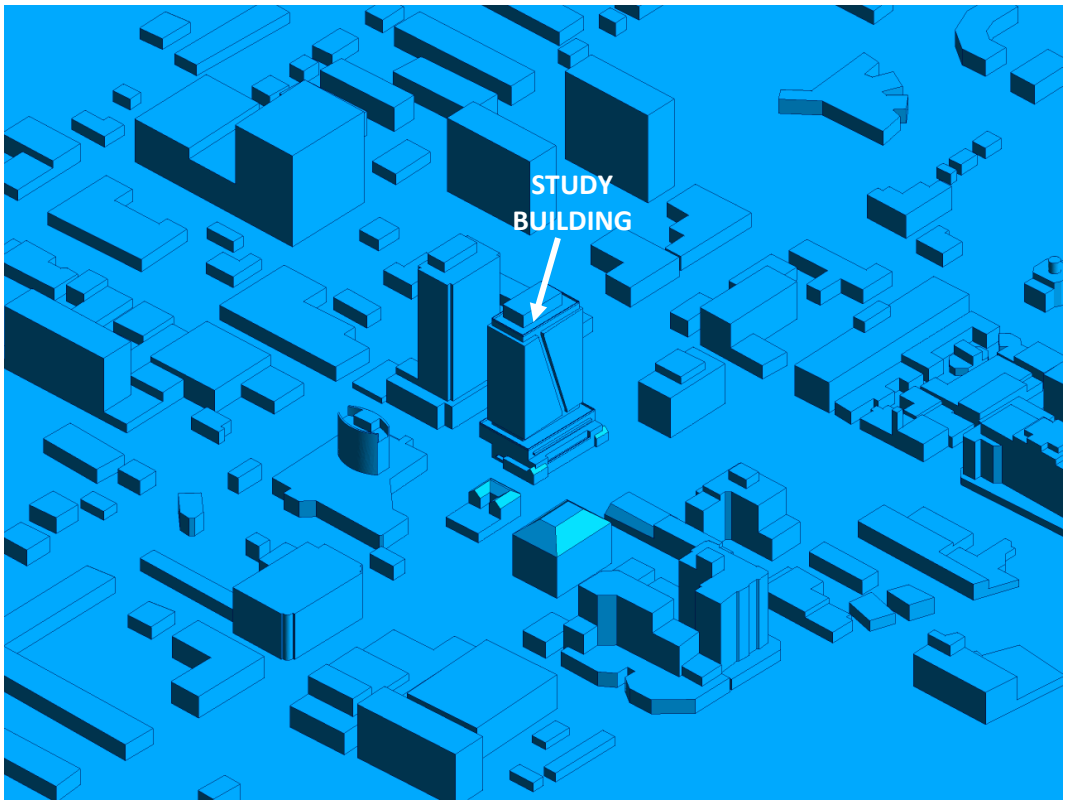



**FIGURE 2A: COMPUTATIONAL MODEL, SOUTH PERSPECTIVE**

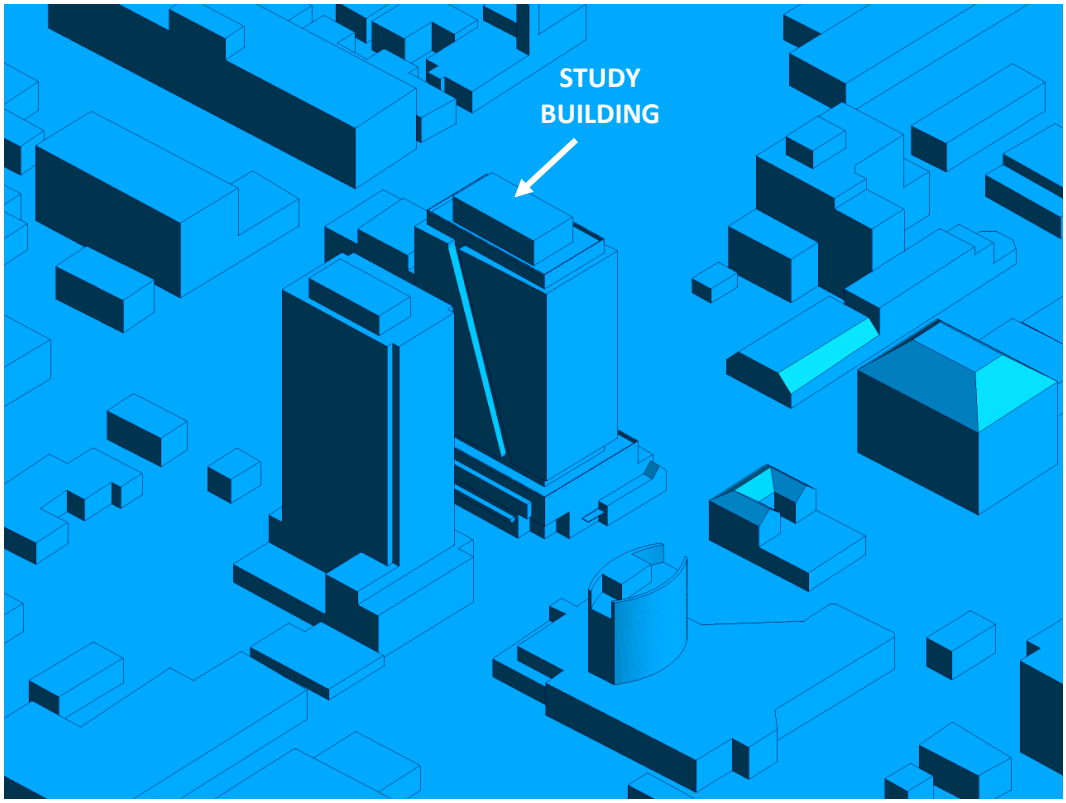



**FIGURE 2B: STUDY BUILDING, WEST PERSPECTIVE**

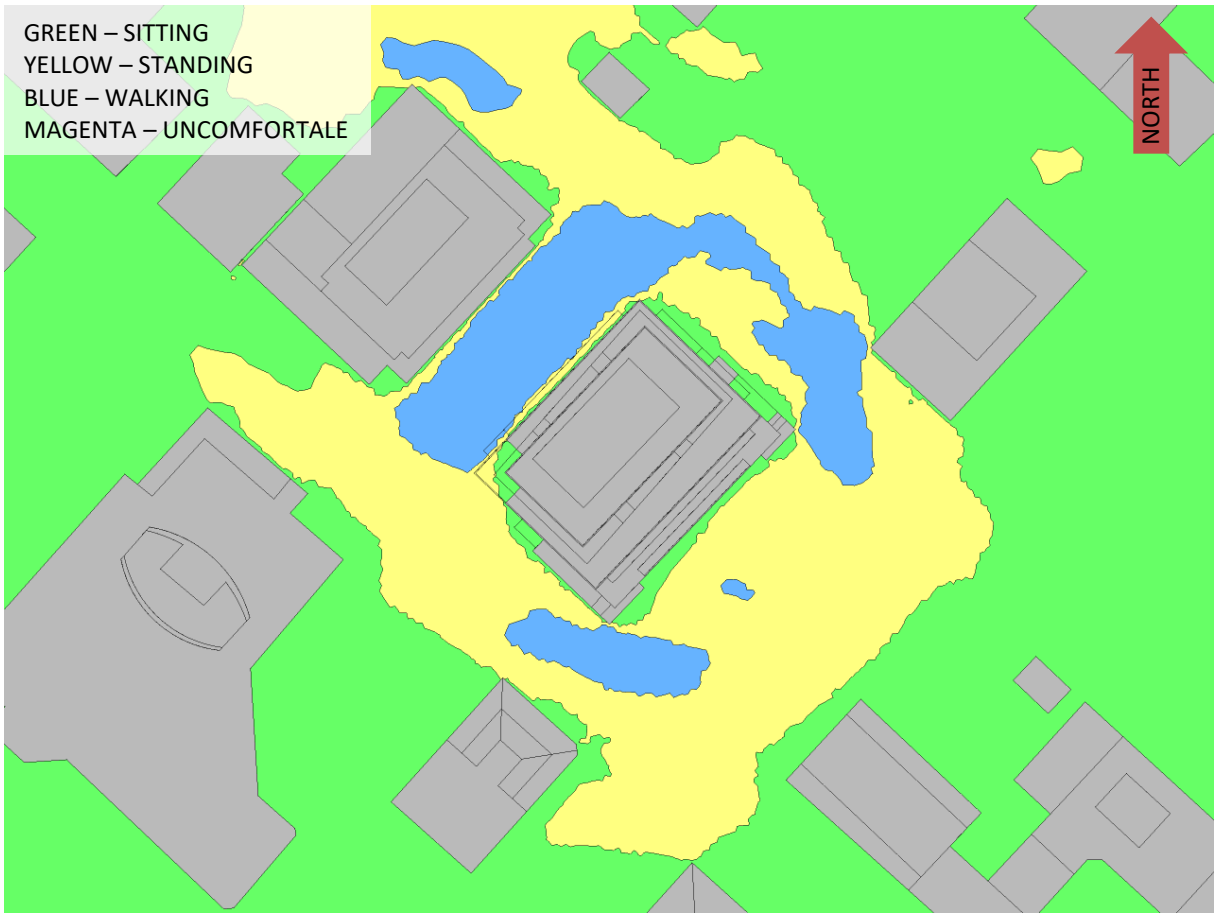
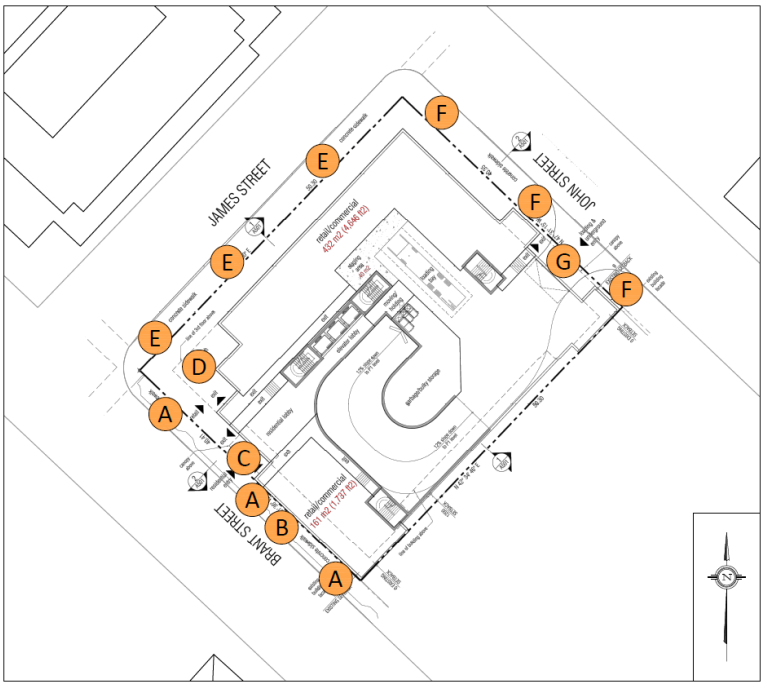



**FIGURE 3A: SPRING – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS**




**409 BRANT STREET – WIND REFERENCE LOCATIONS**

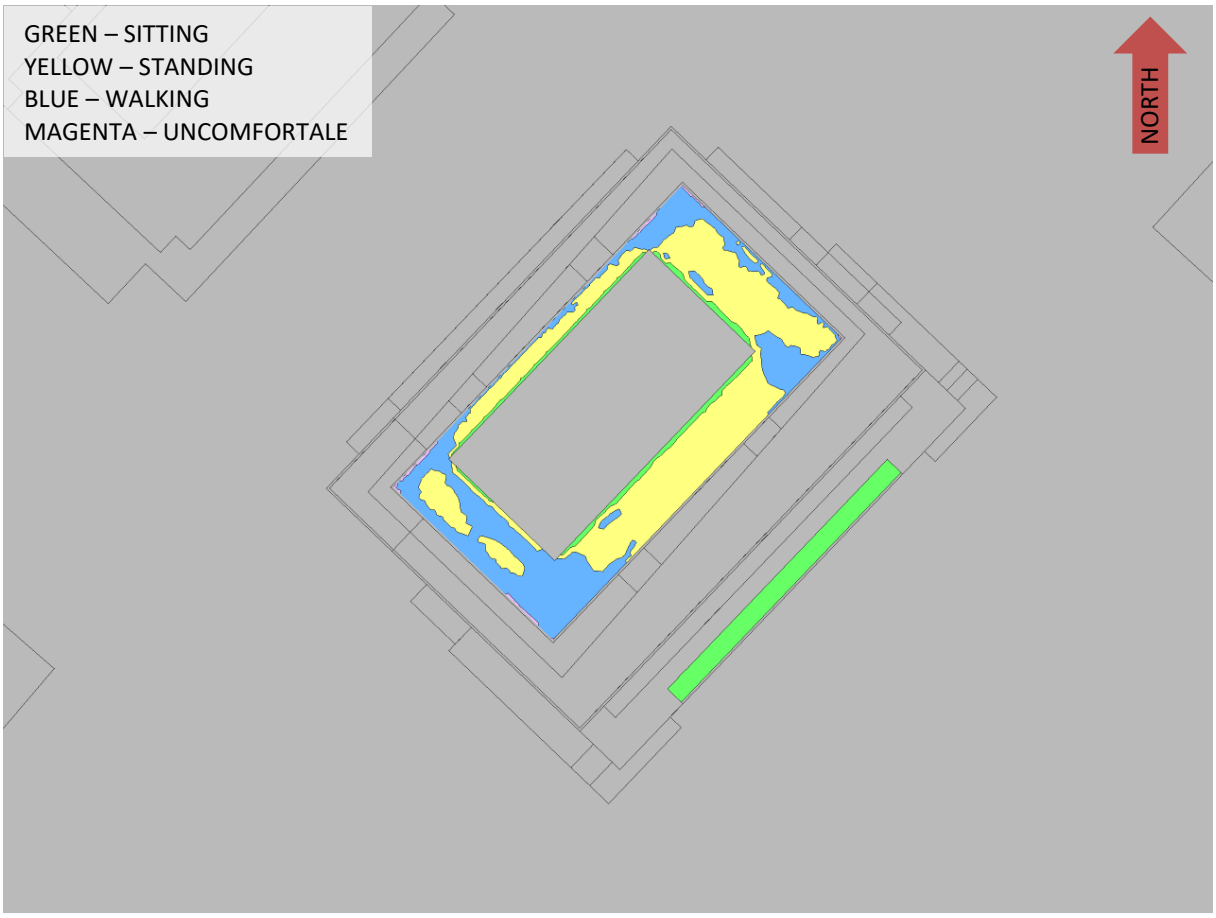
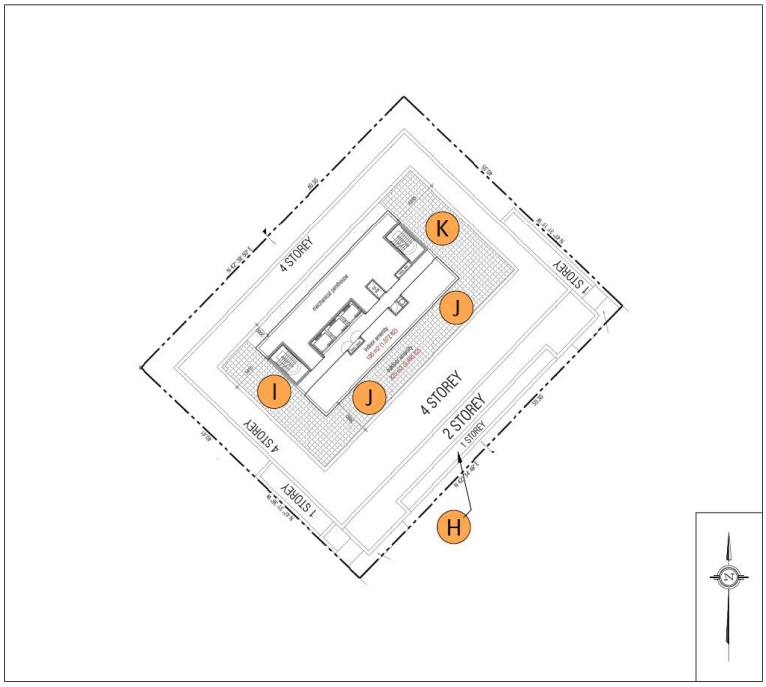


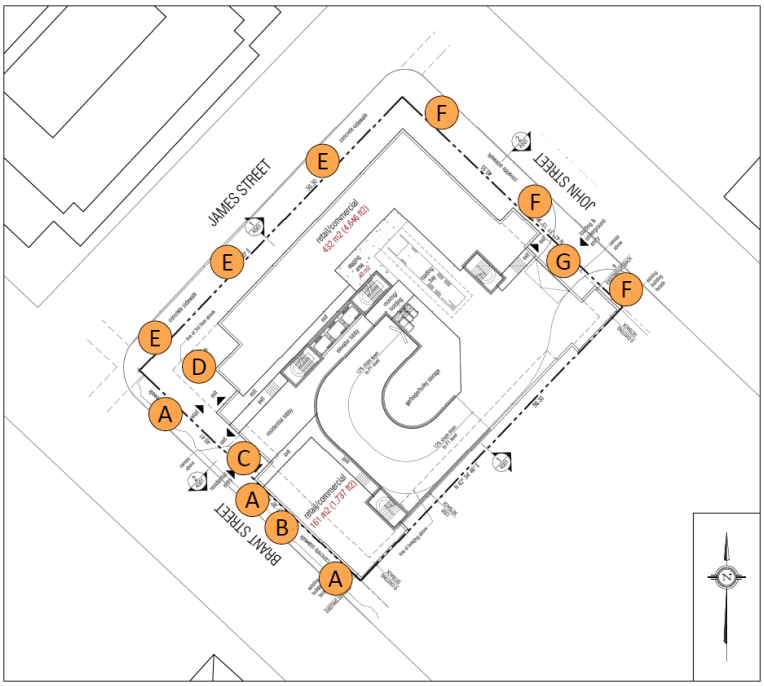

**FIGURE 3B: SPRING – ELEVATED AMENITY AREA WIND CONDITIONS**




**409 BRANT STREET – WIND REFERENCE LOCATIONS**




**FIGURE 4B: SUMMER – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS**




**409 BRANT STREET – WIND REFERENCE LOCATIONS**

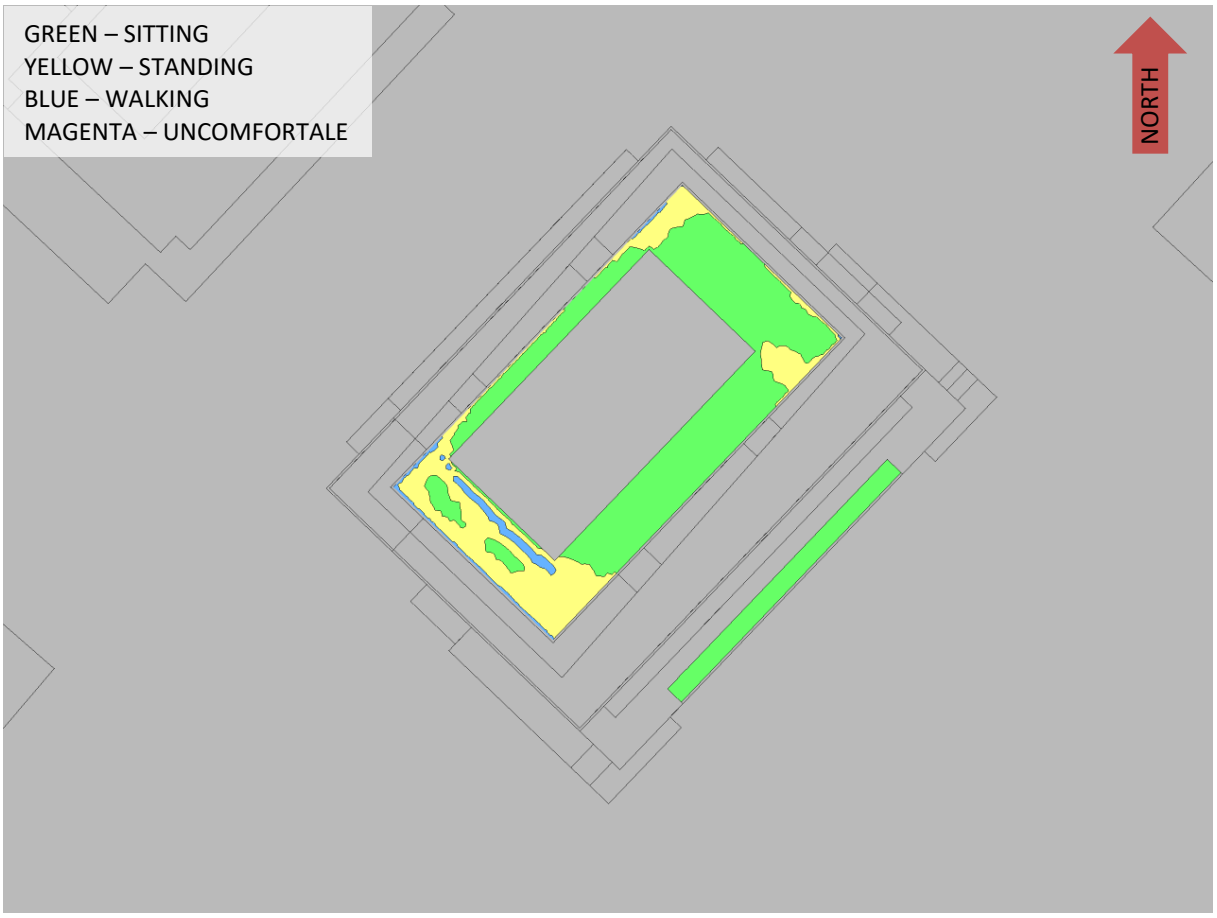
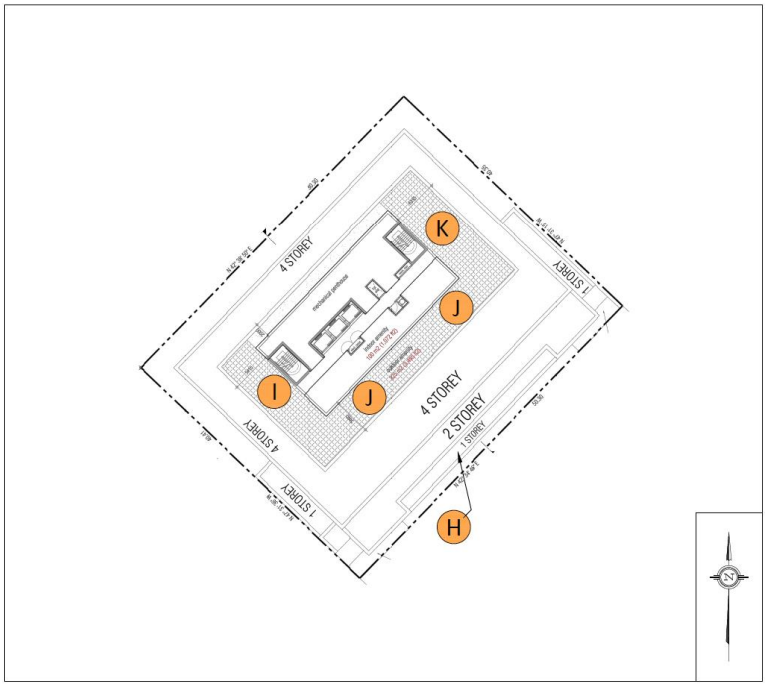



**FIGURE 4B: SUMMER – ELEVATED AMENITY AREA WIND CONDITIONS**




**409 BRANT STREET – WIND REFERENCE LOCATIONS**

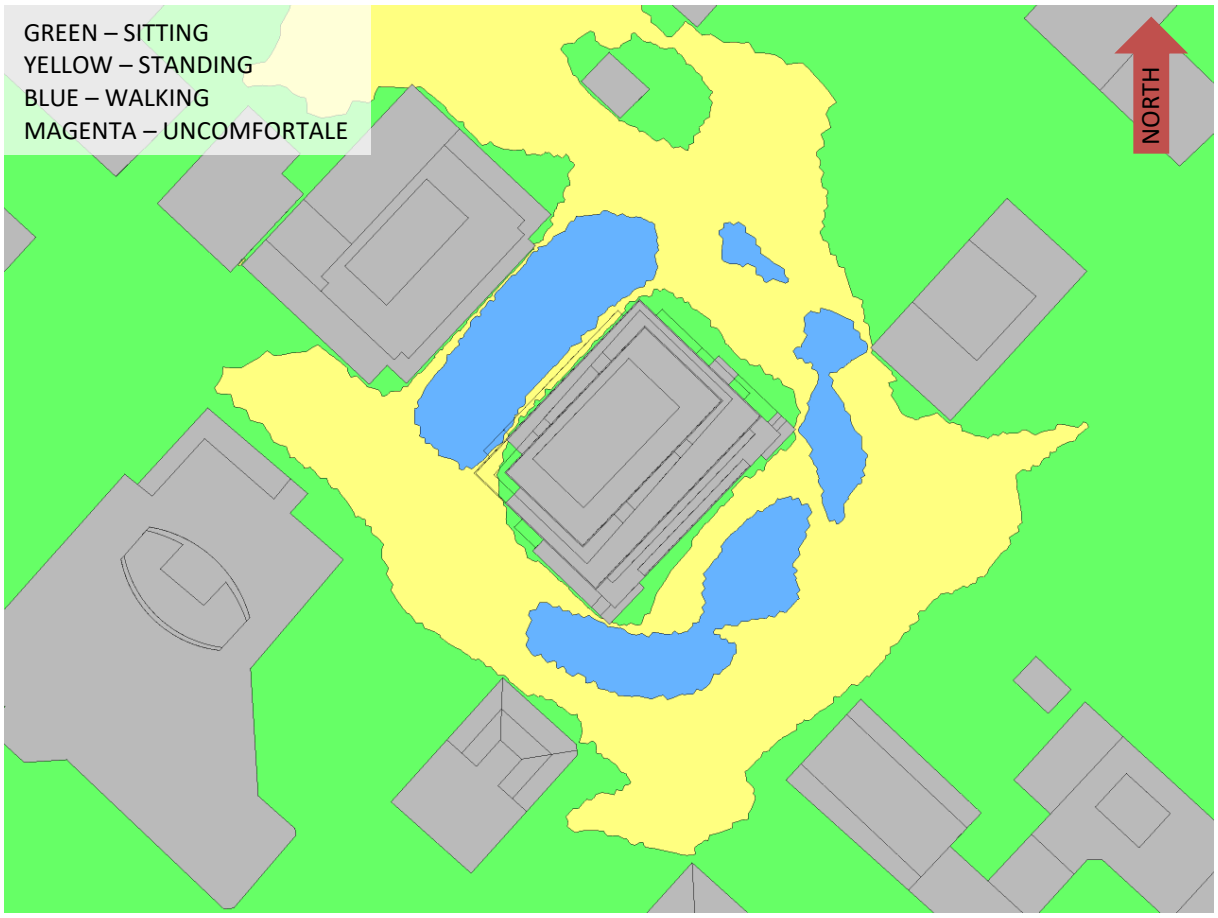
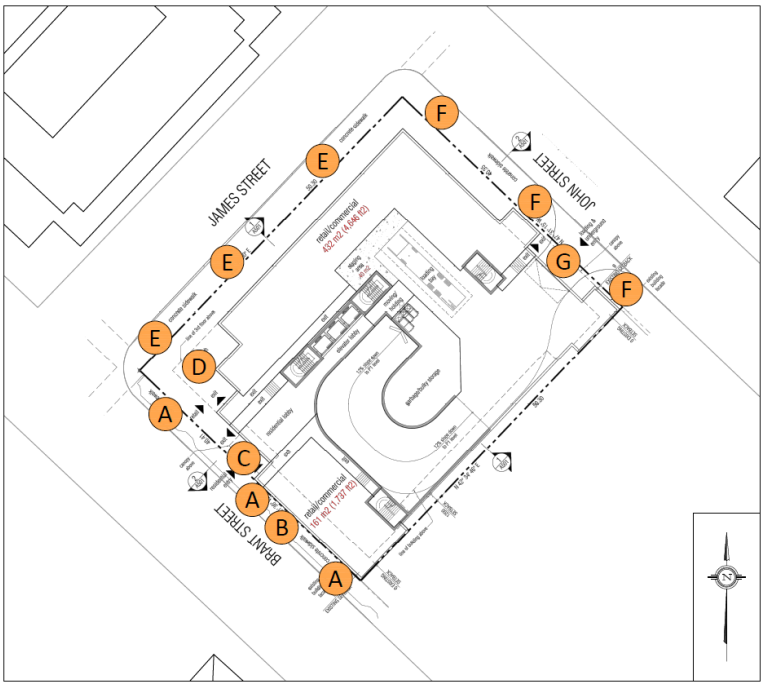



**FIGURE 5A: AUTUMN – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS**




**409 BRANT STREET – WIND REFERENCE LOCATIONS**

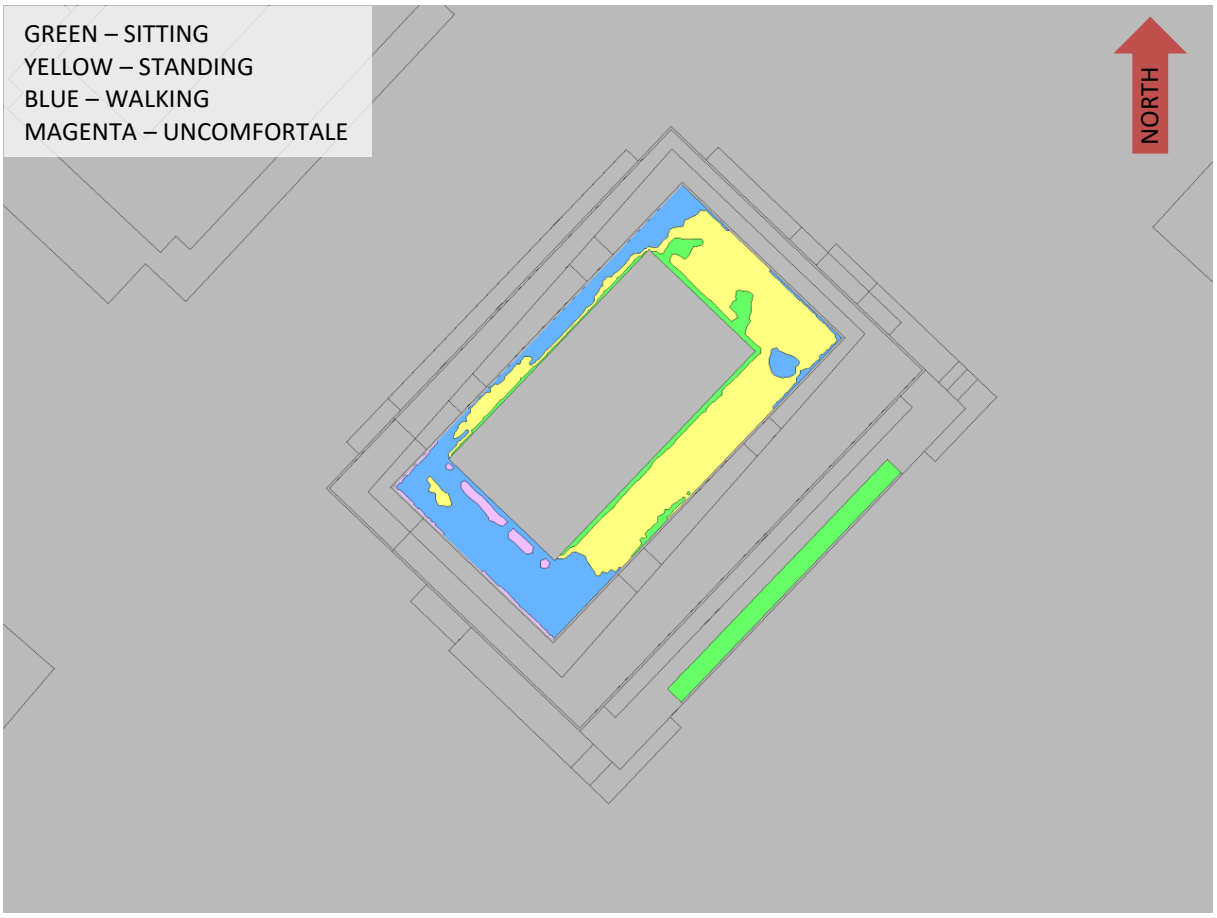
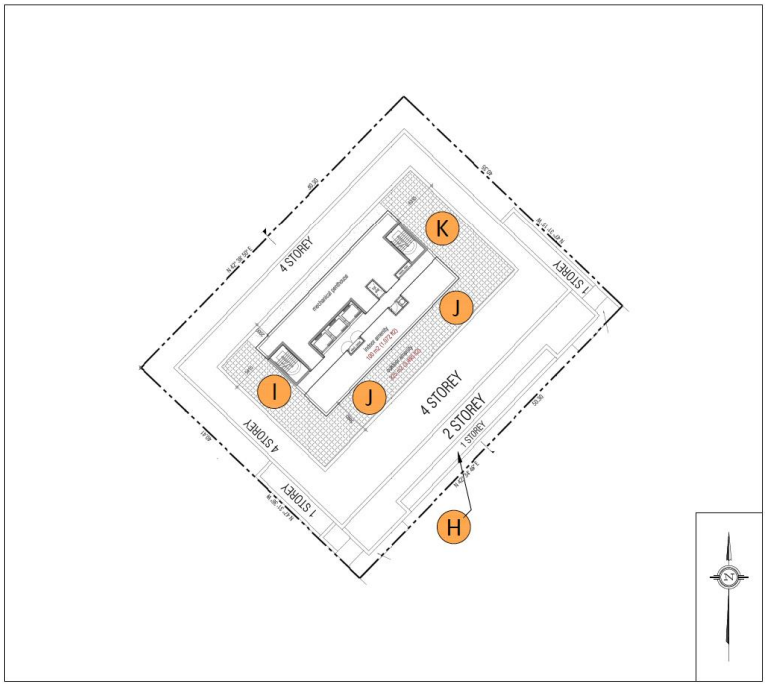



**FIGURE 5B: AUTUMN – ELEVATED AMENITY AREA WIND CONDITIONS**




**409 BRANT STREET – WIND REFERENCE LOCATIONS**

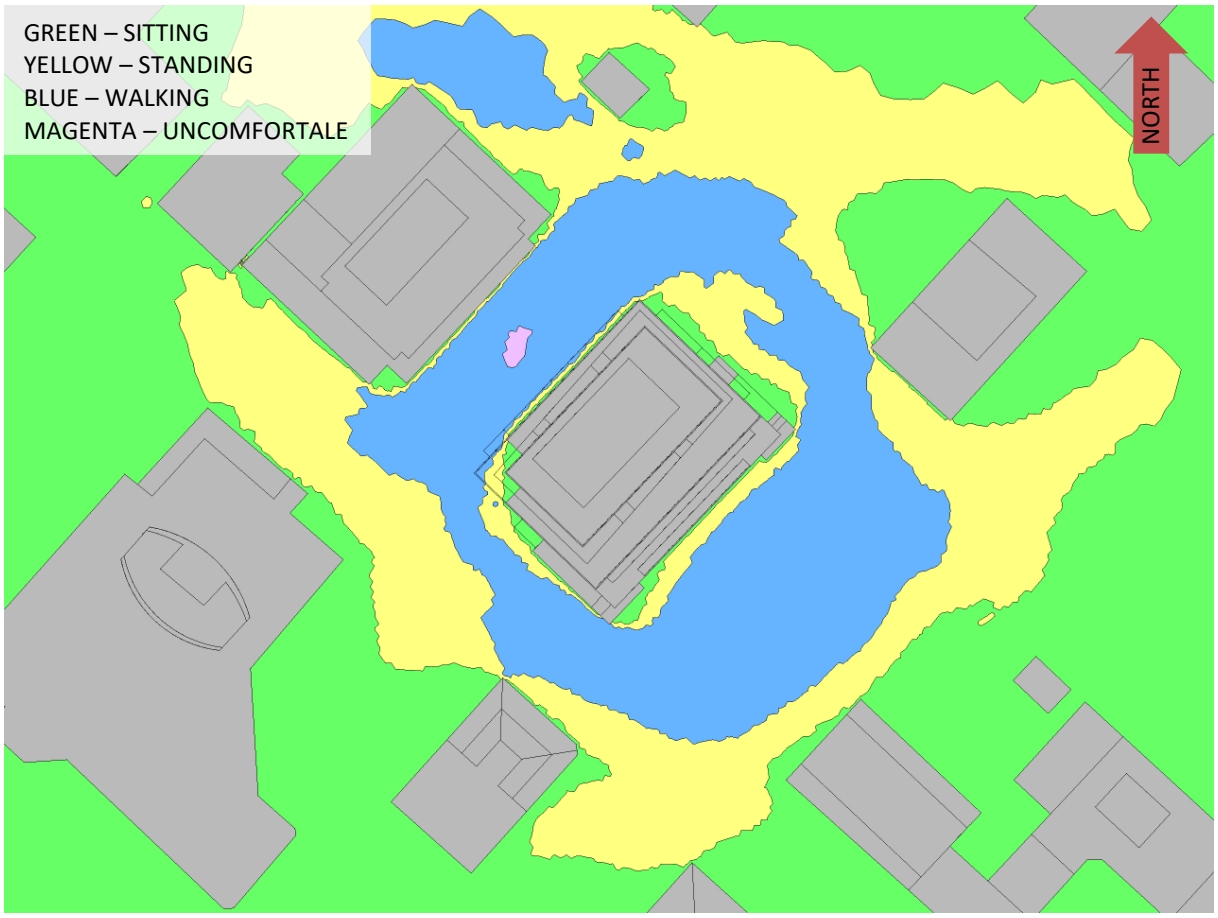
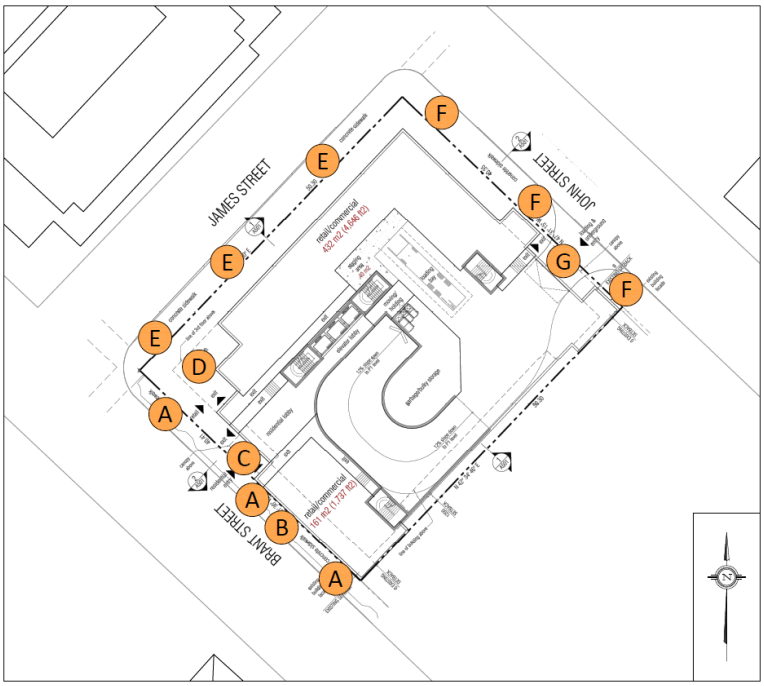



**FIGURE 6A: WINTER – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS**




**409 BRANT STREET – WIND REFERENCE LOCATIONS**

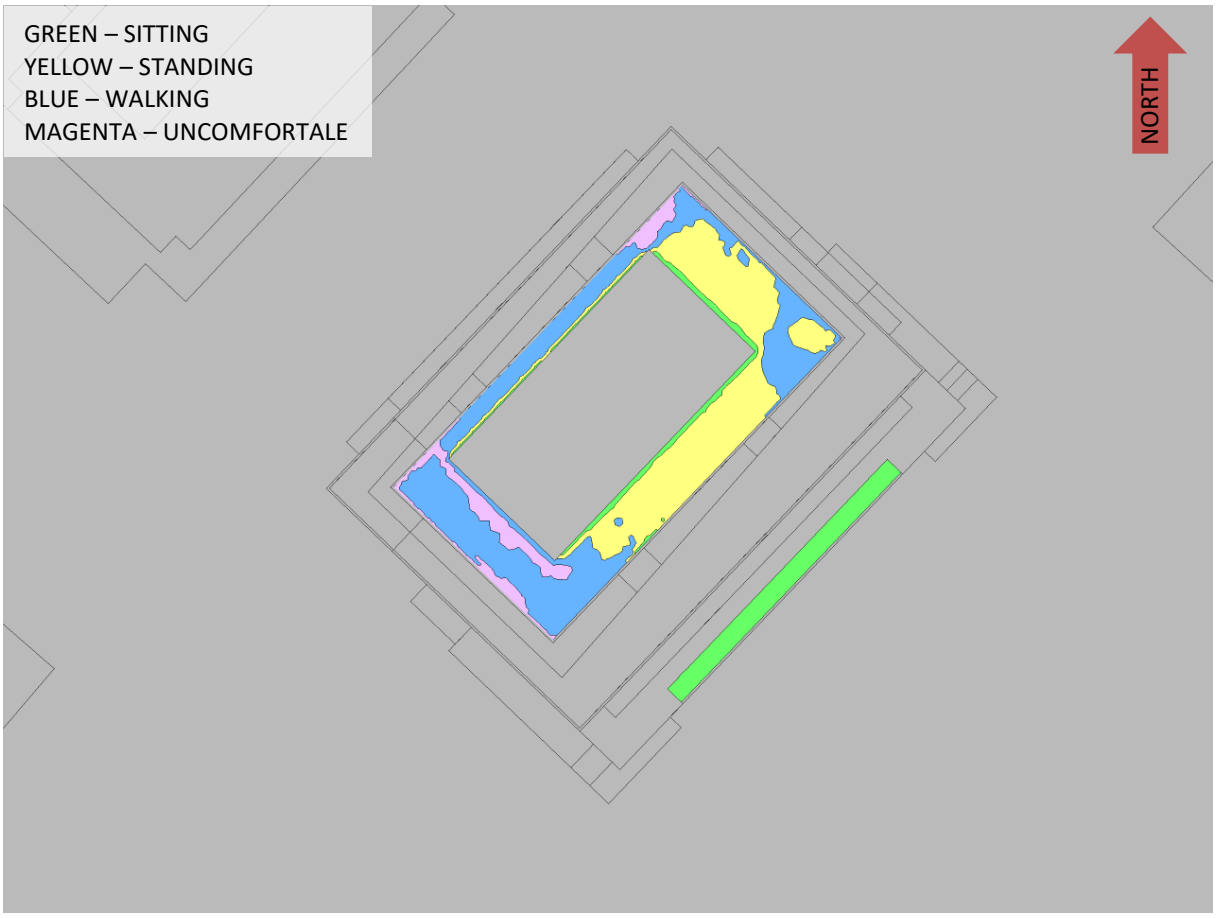
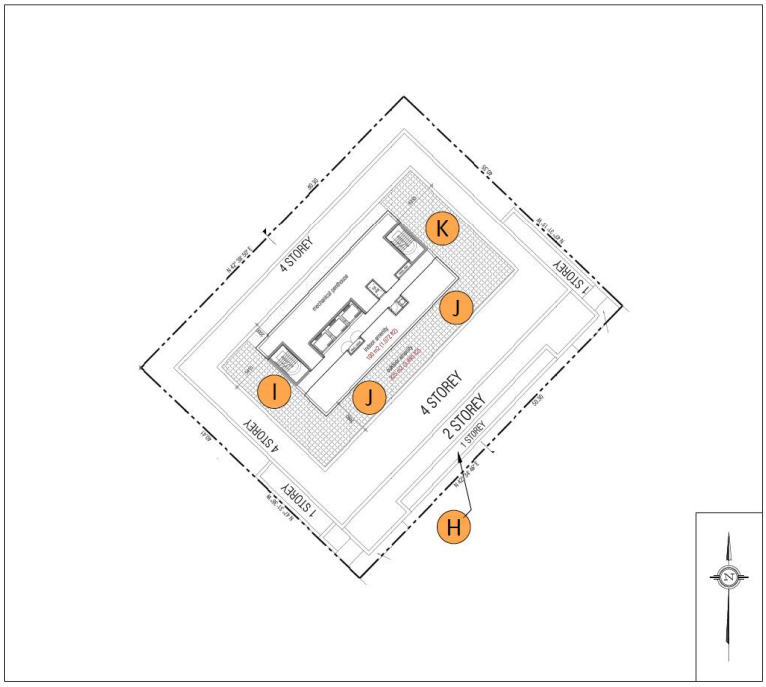



**FIGURE 5B: WINTER – ELEVATED AMENITY AREA WIND CONDITIONS**




**409 BRANT STREET – WIND REFERENCE 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; $\boldsymbol{U}$ = mean wind speed, $\boldsymbol{U_g}$ = gradient wind speed, $\boldsymbol{Z}$ = height above ground, $\boldsymbol{Z_g}$ = depth of the boundary layer (gradient height) and $\alpha$ is the power law exponent.

Figure A1 plots three such profiles for the open country, suburban and urban exposures. The exponent $\alpha$ varies according to the type of terrain; $\alpha$ = 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:

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

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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2. Flay, R.G., Stevenson, D.C., '*Integral Length Scales In An Atmospheric Boundary Layer Near The Ground*', 9th Australian Fluid Mechanics Conference, Auckland, Dec. 1966

3. ESDU, '*Characteristics of Atmospheric Turbulence Near the Ground*', 74030

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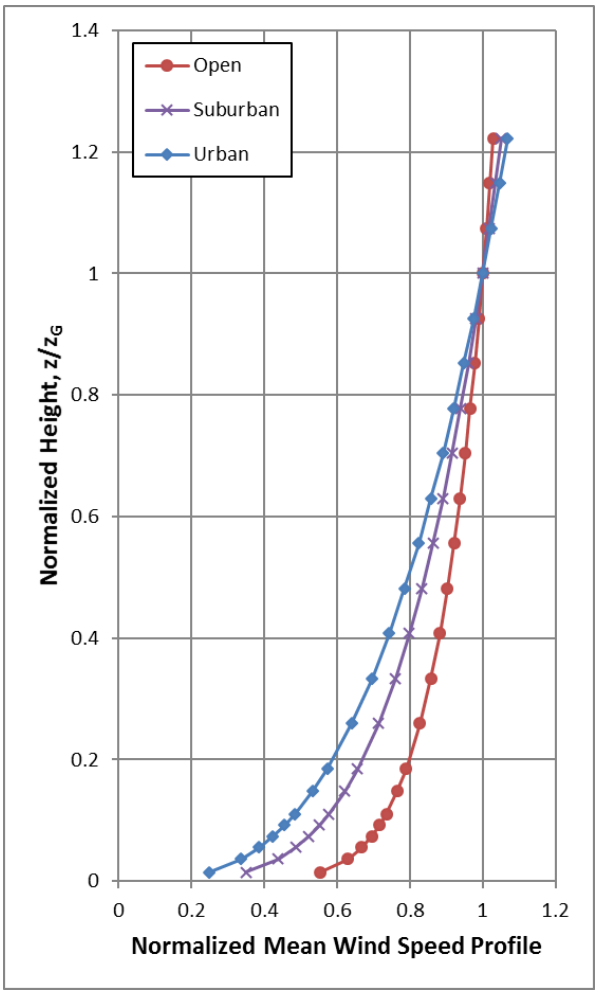




**Figure A1: Mean Wind Speed Profiles**

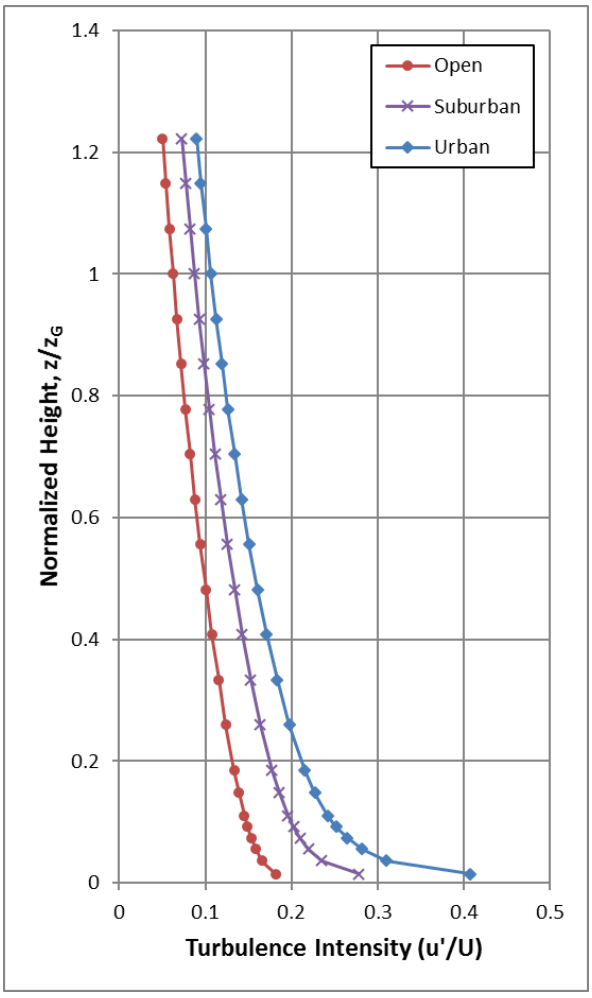



**Figure A2: Turbulence Intensity Profiles**

# 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:

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

Where,

***P (> $U_g$)*** is the probability, fraction of time, that the gradient wind speed ***$U_g$*** is exceeded; ***$\theta$*** 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). ***$A_\theta$*** is the fraction of time wind blows from a 10° sector centered on ***$\theta$***.

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

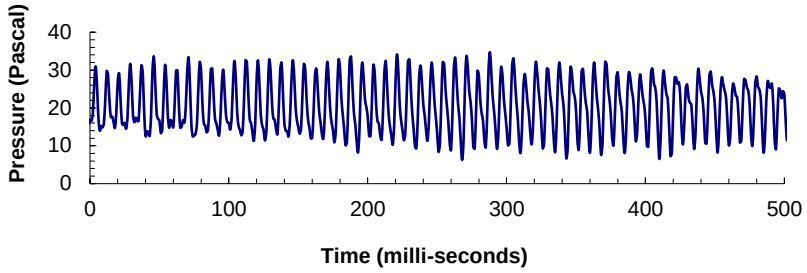
$$P_N(>20) = \Sigma_\theta P\left[\frac{(>20)}{\left(\frac{U_N}{U_g}\right)}\right]$$

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

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 ***$C_\theta$*** and ***$K_\theta$*** 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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