Preliminary Pedestrian Level Wind Study

City Park Redevelopment

Ottawa, Ontario

REPORT: GWE15-068 – CFD PLW

Prepared For:

Stuart Craig
RioCan Management Inc.
2300 Yonge Street, Suite 500
Toronto, Ontario
M4P 1E4

Prepared By:

Joshua Foster, P. Eng., Partner
Steven Hall, M.A.Sc., EIT, Specialist
Vincent Ferraro, M.Eng., P.Eng., Principal

November 11, 2015

EXECUTIVE SUMMARY

This document describes the results of a preliminary pedestrian level wind study undertaken for the proposed mixed-use development, City Park Redevelopment, located at 2280 City Park Drive 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 a statistical model of the Ottawa wind climate, to assess pedestrian comfort at grade level locations within and surrounding the development site. The results derived from these considerations are summarized in the following paragraphs and detailed in the subsequent report.

The work was performed as part of a master plan concept for support of a rezoning application. A simultaneous site plan application is also being submitted for the initial phase of the development, Tower A. This report addresses both a future build-out scenario and the initial phase of the development. The focus of this study is the proposed mixed-use high-rise development where the master plan comprises three residential towers on a connected podium, two stand-alone midrise mixed-use buildings, a two-storey parking structure, and a single storey amenity building. The first phase of development will introduce Tower A on the southeast corner of the site. The existing restaurant building and half of the existing retail buildings would remain until subsequent phases of construction. Our work is based on industry standard computer simulation techniques and data analysis procedures, City of Ottawa Terms of Reference for Wind Analysis, architectural drawings provided by Barry J. Hobin Architects., dated October 7, 2015, surrounding street layouts and building massing, as well as recent site imagery.

A complete summary of the predicted wind conditions for the fully developed site and Phase 1 development are presented in Section 5 of this report. Pedestrian comfort conditions are summarized visually in Figures 3A to 6B for the full build-out scenario and in 8A to 11B for Phase 1, following the main text of this report. Based on CFD test results, interpretation and experience with similar developments, we conclude that the majority of grade-level areas within and surrounding the development site will be acceptable for the intended pedestrian uses on an annual and seasonal basis. Suitable wind conditions around main building entrances can be maintained by selecting door locations away from corners of the buildings and within the middle 70% of the façades.

Wind conditions over elevated roof surfaces of the podia and towers have been found to vary from sitting to walking. Any rooftop areas planned for seating can be selected judiciously to minimize the extent of mitigation, and then treated with landscape features including wind barriers, as required, to achieve conditions suited to the intended uses. In generic terms, wind barriers may comprise vertical transparent / translucent material extending 1.6 to 2.4 meters above the roof surface, or equivalently a dense arrangement of typically coniferous plantings, or a combination of the two. Amenity spaces would be selected and mitigated as required by cooperation among the design team members.

TABLE OF CONTENTS

		PAGE
1.	INTRODUCTION	1
2.	TERMS OF REFERENCE	1
3.	OBJECTIVES	2
4.	STUDY METHODOLOGY	2
	4.1 Context Modelling	2
	4.2 Wind Speed Measurements	3
	4.3 Historical Wind Data Analysis	3
	4.4 Pedestrian Comfort Guidelines	6
5.	RESULTS	9
6.	SUMMARY AND RECOMMENDATIONS	10

FIGURES

APPENDICES:

Appendix A: Simulation of the Natural Wind

Appendix B: Pedestrian Level Wind Measurement Methodology

1. INTRODUCTION

Gradient Wind Engineering Inc. (GWE) was retained by RioCan Management Inc. to undertake a pedestrian level wind study (PLW) to satisfy rezoning and site plan approval requirements for the proposed mixed-use development, City Park, located at 2280 City Park Drive Ottawa 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. When combined with meteorological statistics for the site, the raw data obtained from the CFD simulations are used to predict pedestrian comfort. The results and recommendations derived from these considerations are summarized in the following paragraphs and detailed in the subsequent report. Our work is based on architectural drawings provided by Barry J. Hobin Architects Inc., dated October 7, 2015, as well as context data obtained from aerial images and City of Ottawa base mapping to obtain site exposure information.

2. TERMS OF REFERENCE

The focus of this study is a proposed mixed-use high rise development where the master plan comprises three residential towers linked by a common podia, two stand-alone midrise mixed-use buildings, a single storey amenity building, and a parking structure. The three towers will be located on the south edge of the property. The east building, Tower A, will be the tallest building on site at 30 storeys. The central tower, Tower B, will be 25 storeys and the west building, Tower C, will rise 20 storeys. Midrise buildings, Buildings D and E, will rise four-storeys and are located on the north edge of the site. The amenity building, Building F, is located to the southeast of Building E. A two-storey parking structure is located to the west of Tower C. At grade in the centre of the development will be a playground and visitor parking. Along the north face of the towers will be terraced plantings, leading to the main building entrances. Tenant surface parking will be located to the south and east of the towers. For this study, it was assumed roof surfaces on the towers and podium could potentially be used as terraces.

Phase 1 of the development will consist of removing half of the existing commercial retail building to allow for Tower A to be constructed. The existing restaurant building to the north would remain, along with most of the existing surface parking.

From a wind comfort perspective, areas of interest associated with the development include pedestrian sidewalks and building entrances, as well as open landscaped areas and plazas. Figure 1 illustrates the context plan, while Figures 2A and 2B illustrate the computational model used to conduct the study for the full site build-out. The concept model for Phase 1 is illustrated in Figures 7A and 7B

3. OBJECTIVES

The principal objectives of this study are to: (i) determine pedestrian level comfort and safety conditions at key outdoor areas; (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. STUDY METHODOLOGY

The approach followed to quantify pedestrian wind conditions over the site is based on Computational Fluid Dynamics (CFD) simulations of wind speeds at selected locations on a scale model within a virtual environment, meteorological analysis of the Ottawa wind climate, and synthesis of computational data with industry accepted comfort guidelines. The following sections describe the analysis procedures, including a discussion of the pedestrian comfort guidelines.

4.1 Context Modelling

A PLW study was performed to determine the influence of the wind environment 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 McDonald-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 twelve (12) wind directions: 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, and 330°. The CFD simulation model was centered on the study building, complete with surrounding massing within a diameter of approximately 450 meters (m).

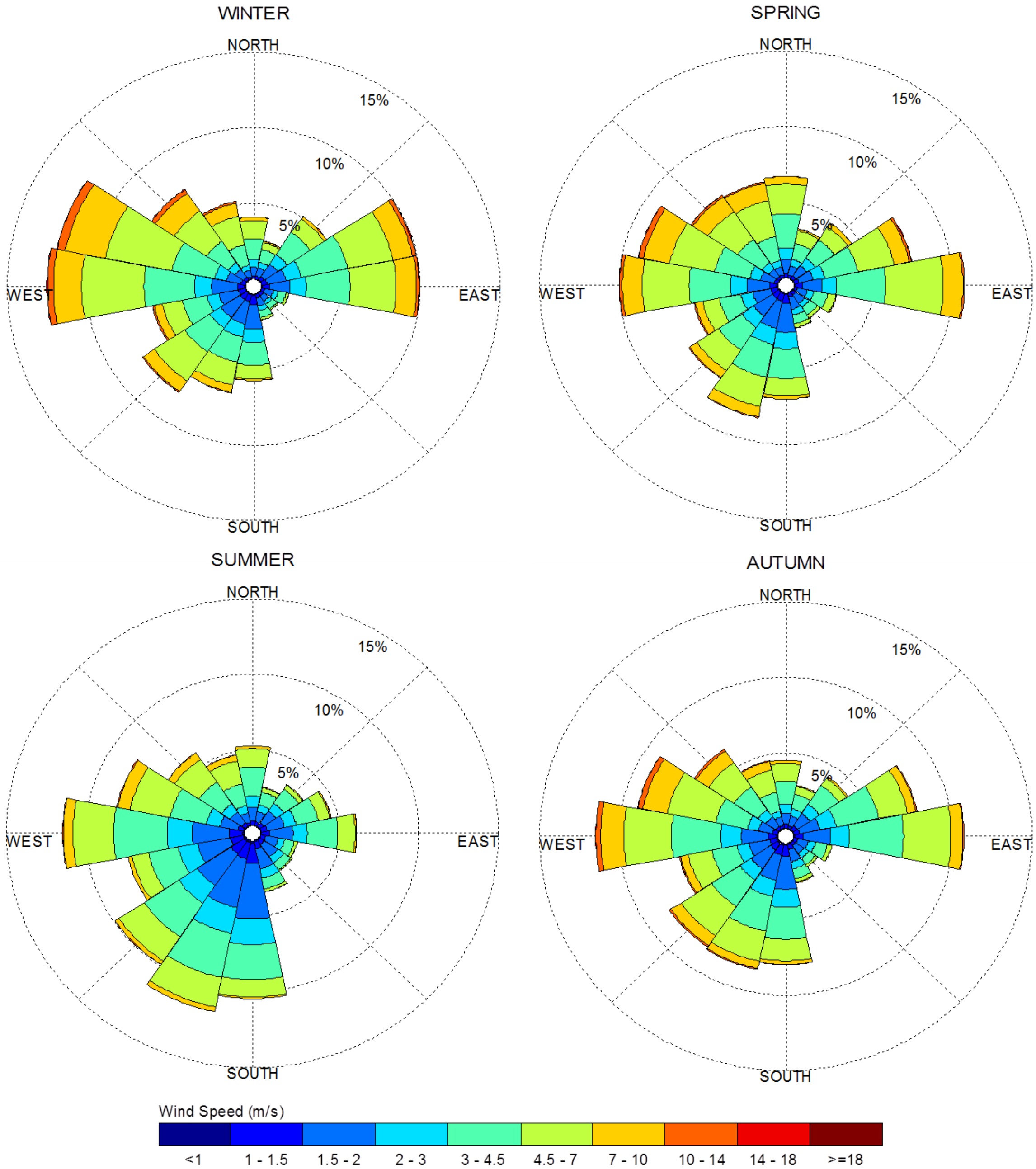
Mean and peak wind speed data obtained over the study site for each wind direction were interpolated to thirty-six (36) wind directions at 10° intervals, representing the full compass azimuth. Measured wind speeds approximately 1.5 m above local grade, as well as 1.5 m above the amenity terraces on the second, third, and tenth levels, 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 in both CFD and wind tunnel environments.

4.3 Historical Wind Data Analysis

A statistical model for winds in Ottawa was developed from approximately forty years of hourly meteorological wind data recorded at Ottawa 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 wind speeds and directions in meters per second. 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 as the length of the bar where the given bar has the largest length. For Ottawa, the most common winds occur for west and east quadrants; and the most common wind speeds are below 10 m per second. However, it is noted that the most prominent wind direction for higher wind speeds originates from the west during the winter months. The directional preference and relative magnitude of wind speed changes somewhat from season to season, with the summer months displaying the calmest winds relative to the remaining seasonal periods. 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, OTTAWA 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, based on the City of Ottawa's Terms of Reference for Wind Analysis, 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) Strolling; (iv) Walking; (v) Uncomfortable; and (vi) Dangerous. More specifically, the comfort classes, associated wind speed ranges, and limiting guidelines are summarized as follows:

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

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

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

(iv) **Walking** – Average gust wind speeds less than or equal to 30 km/h, occurring at least 80% of the time. The corresponding equivalent mean wind speed is approximately 20 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** – Average gust wind speeds greater than or equal to 90 km/h, occurring at least 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.

Average 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 average 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, for instance, wind speeds of 14 km/h were exceeded for more than 20% or 30% 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 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 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. An overview of common pedestrian location types and their desired comfort classes are summarized below.

DESIRED PEDESTRIAN COMFORT CLASSES FOR VARIOUS LOCATION TYPES

Location Types	Desired Comfort Classes
Major Building Entrance	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

Following the comparison, the location is assigned a descriptor that indicates the suitability of the location for its intended use. The suitability descriptors are summarized as follows:

- **Acceptable:** The predicted wind conditions are suitable for the intended uses of the associated outdoor spaces without the need for mitigation.
- **Acceptable with Mitigation:** The predicted wind conditions are not acceptable for the intended use of a space; however, following the implementation of typical mitigation measures, the wind conditions are expected to satisfy the required comfort guidelines.
- **Mitigation Testing Recommended:** The effectiveness of typical mitigation measures is uncertain, and additional wind tunnel testing is recommended to explore other options and to ensure compliance with the comfort guidelines.
- **Incompatible:** The predicted wind conditions will interfere with the comfortable and/or safe use of a space, and cannot be feasibly mitigated to acceptable levels

5. RESULTS

The foregoing discussion of predicted pedestrian wind conditions for the full build-out of 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 elevated roof surfaces which have the potential to be used as amenity terraces. Wind conditions for Phase 1 of the development, Tower A, are illustrated in Figures 8A to 11B. The colour contours indicate predicted regions of the various comfort classes. Wind conditions comfortable for sitting, or more sedentary activities, is represented by the colour green, standing is represented by yellow, strolling is represented as pink, walking is represented by blue, and grey indicates wind conditions considered uncomfortable for walking. The following discussion is related to the full site build-out. Following the main discussion is a commentary on the variations in wind conditions would be expected for the Phase 1 of development.

Sidewalks along City Park Drive (Tag A): To the north of the development, pedestrian sidewalks along City Park Drive are expected to be suitable for standing throughout the year, with some areas more suited to strolling activities during the spring and winter. The noted conditions are considered acceptable for the intended uses of the space.

Parking Area to the South of the Development (Tag B): The sidewalks along the parking area to the south of the development will be suitable for strolling or better throughout the year, which is acceptable for the intended use of the space

Pedestrian Plazas at the Base of Towers A and C (Tag C): The pedestrian plazas adjacent to Towers A and C will experience wind conditions suitable for sitting during the summer and standing the remainder of the year. These conditions are considered acceptable for the intended use of the space.

Public Park / Playground (Tag D): The park / playground south of Building E will experience conditions over most of the area suitable for standing in the summer and autumn, while in spring and winter conditions will be more suited to strolling activities. Throughout the year, wind conditions will be acceptable for the intended use of the space.

Potential Building Entrances: Wind conditions along the north façades of Towers A to C will be acceptable for sitting during the summer and standing the rest of the year. These calm conditions are ideal locations for primary building entrances. Conditions along the south side of the towers will be suitable for strolling or better and acceptable for secondary entrances. Wind conditions around the perimeter of Buildings D, E and F will be appropriate for standing or better during the four seasons and considered acceptable for the intended use of the space. As a general rule entrances should be located away from the corners of buildings to avoid potentially winder conditions.

Potential Rooftop Terraces: Wind conditions on elevated roof surfaces of the podia and towers, have been found to vary from sitting to walking. Any rooftop areas planned for seating can be selected judiciously to minimize the extent of mitigation, and then treated with landscape features including wind barriers as required to achieve conditions suited to the intended uses. In generic terms, wind barriers may comprise vertical transparent / translucent material extending 1.6 to 2.4 m above the roof surface, or equivalently a dense arrangement of typically coniferous plantings. Amenity spaces can be selected and mitigated as required by cooperation among the design team members.

Phase 1: For the initial site plan configuration with only the construction of Tower A, conditions around the site will be similar to the conditions for the full build-out scenario. Conditions at the corners of the building will be slightly windier for the Phase 1 scenario; however, grade level wind conditions will be acceptable for the intended use of the spaces across the site. Similarly for the terraces, moderately windy conditions are expected and areas intended for sitting will require mitigation.

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 were found to experience wind conditions that are considered unsafe.

6. SUMMARY AND RECOMMENDATIONS

This document describes the results of a pedestrian level wind study undertaken for the City Park Redevelopment, a proposed mixed-use high rise development located in Ottawa, Ontario. The work was performed as part of a master plan concept for support of a rezoning and site plan application, and was based on industry standard computer simulation techniques and data analysis procedures.

Based on CFD test results, interpretation and experience with similar developments, we conclude that the majority of grade-level areas within and surrounding the development site will be acceptable for the intended pedestrian uses on an annual and seasonal basis. Suitable wind conditions around main building entrances can be maintained by selecting door locations away from corners of the buildings and within the middle 70% of the façades.

Wind conditions over elevated roof surfaces of the podia and towers have been found to vary from sitting to walking. Any rooftop areas planned for seating can be selected judiciously to minimize the extent of mitigation, and then treated with landscape features including wind barriers, as required, to achieve conditions suited to the intended uses. In generic terms, wind barriers may comprise vertical transparent / translucent material extending 1.6 to 2.4 m above the roof surface, or equivalently a dense arrangement of typically coniferous plantings, or a combination of the two. Amenity spaces would be selected and mitigated as required by cooperation among the design team members. Given the moderate wind conditions, any local mitigation necessary can be introduced incrementally coinciding with the introduction of future buildings.

Wind conditions related to Phase 1 of the development are expected to be similar to the wind conditions experienced for the full site build-out. Near building corners, slightly moderate wind conditions are expected; however, conditions at grade are expected to be acceptable for the intended use of each space.

Of particular importance, excluding anomalous localized storm events such as tornadoes and downbursts, no areas over the study site are considered unsafe.

This concludes our assessment and report. If you have any questions or wish to discuss our findings, please advise us. In the interim, we thank you for the opportunity to be of service.

Yours truly,

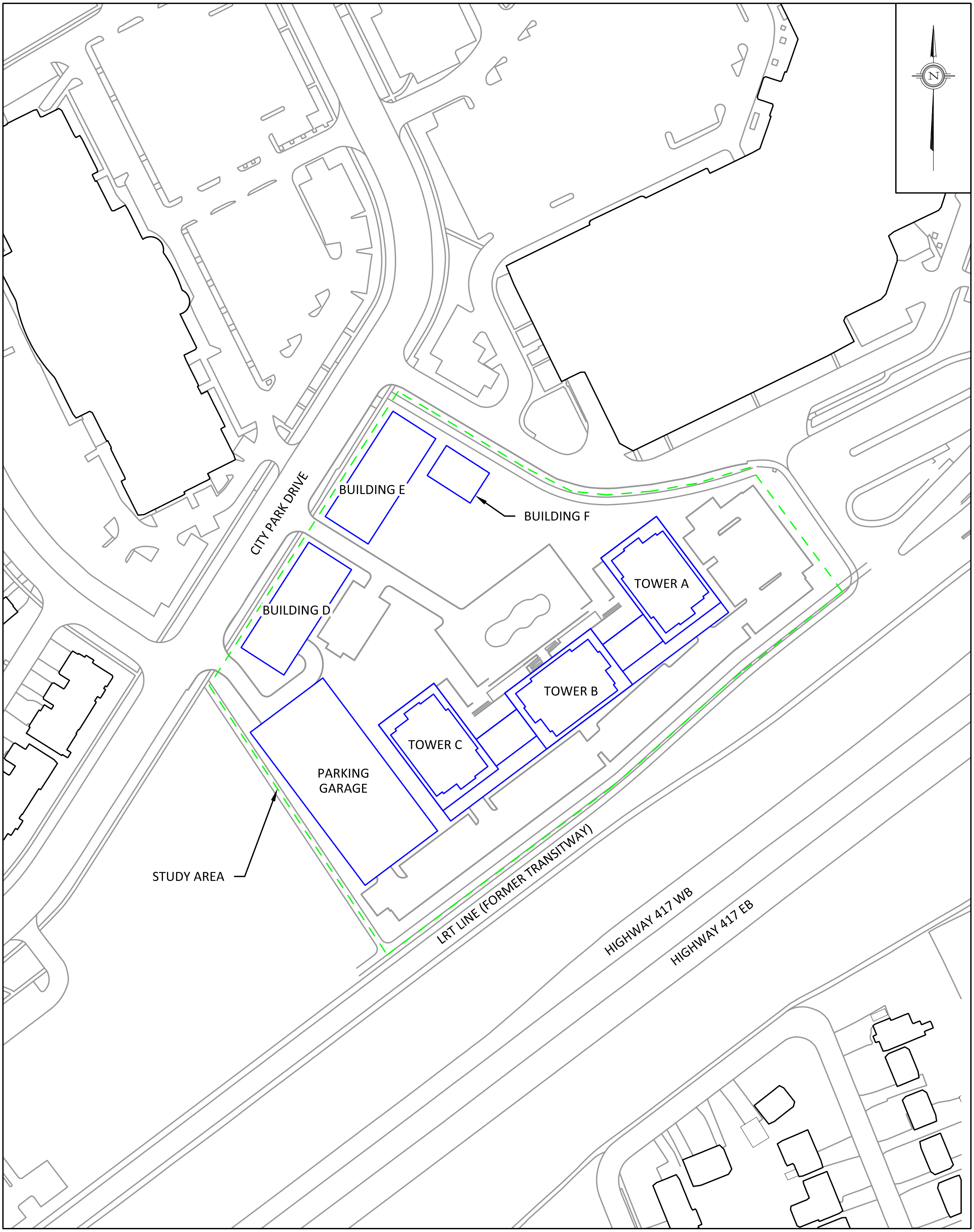
Gradient Wind Engineering Inc.

LICENSED PROFESSIONAL ENGINEER
J. R. FOSTER
100155655
Dec 7, 2015
PROVINCE OF ONTARIO

Joshua Foster, P.Eng.
Partner

Steven Hall, M.A.Sc., EIT.
CFD Specialist

Vincent Ferraro, M.Eng., P.Eng.
Principal
GWE15-068-CFD PLW



GRADIENT WIND ENGINEERING INC

127 Walgreen Road
Ottawa, Ontario
(613) 836 0934

PROJECT	CITY PARK MIXED USE DEVELOPMENT - PLW STUDY		
SCALE	1:2000 (APPROX.)	DRAWING NO.	GWE15-068-1
DATE	NOVEMBER 10, 2015	DRAWN BY	M.L

DESCRIPTION

FIGURE 1:
SITE PLAN AND SURROUNDING CONTEXT

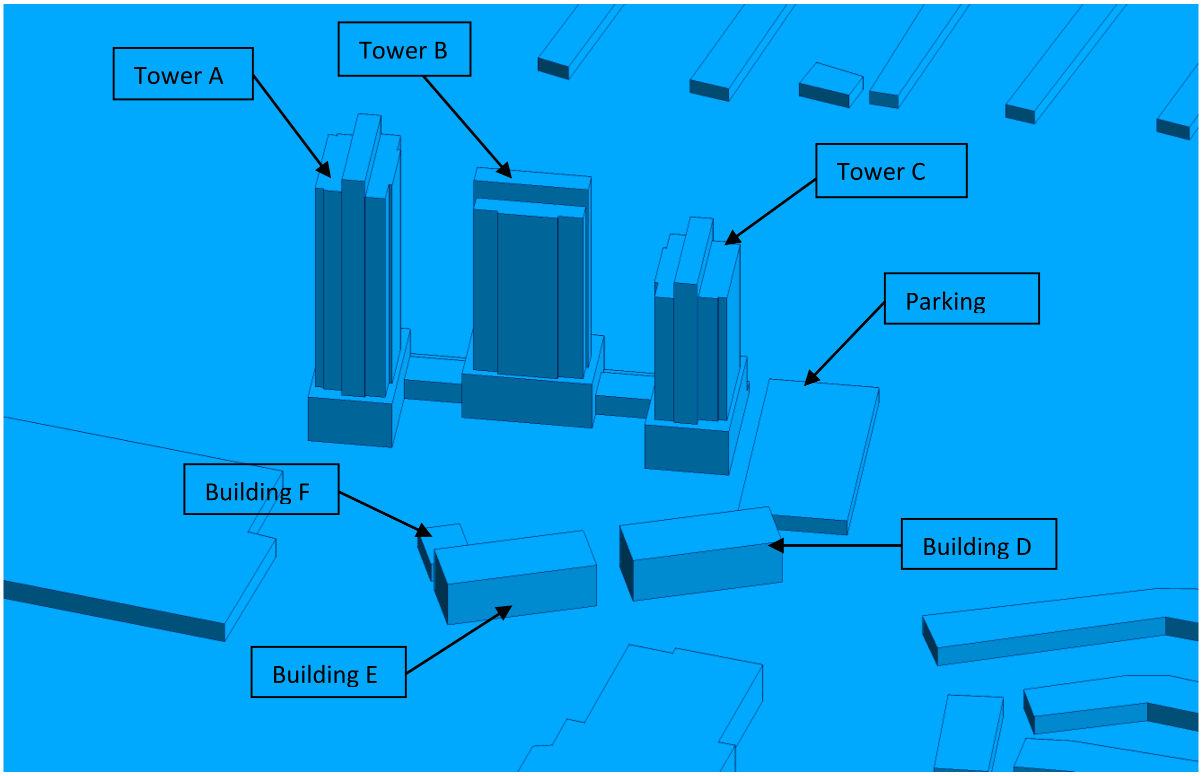


FIGURE 2A: COMPUTATIONAL MODEL FULL SITE BUILD-OUT, NORTHWEST PERSPECTIVE

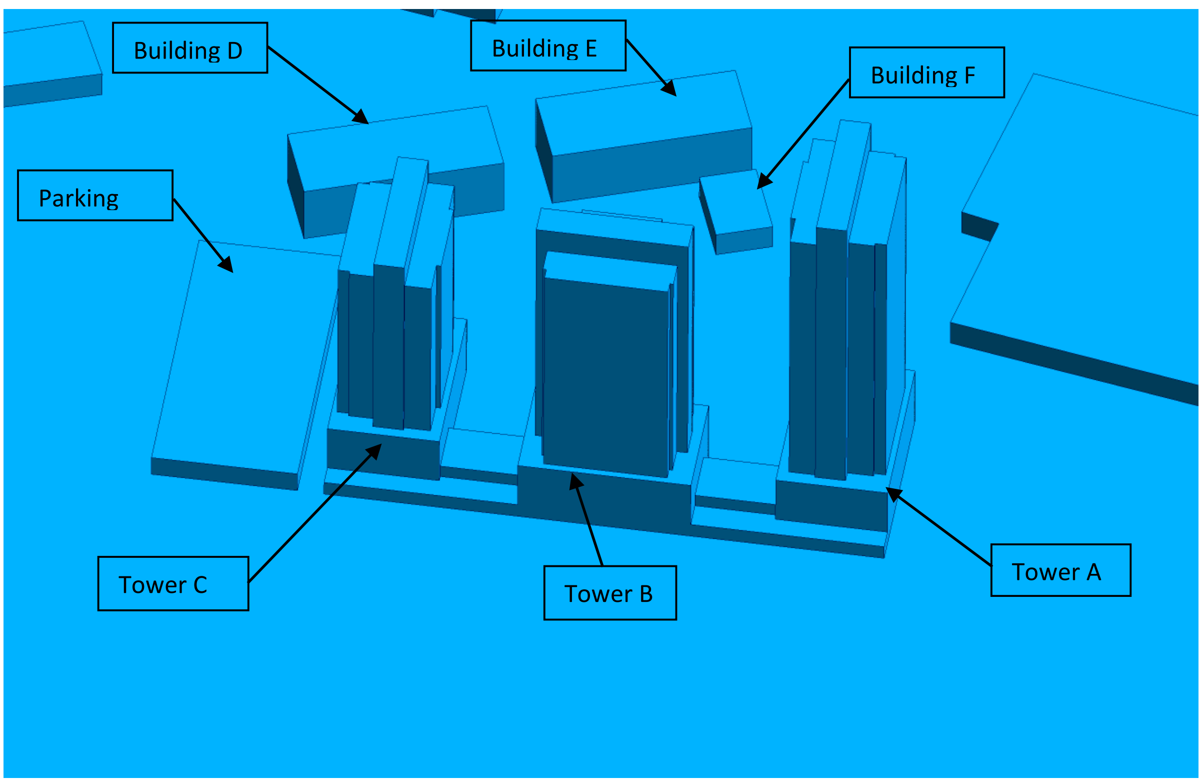


FIGURE 2B: COMPUTATIONAL MODEL FULL SITE BUILD-OUT, SOUTHEAST PERSPECTIVE

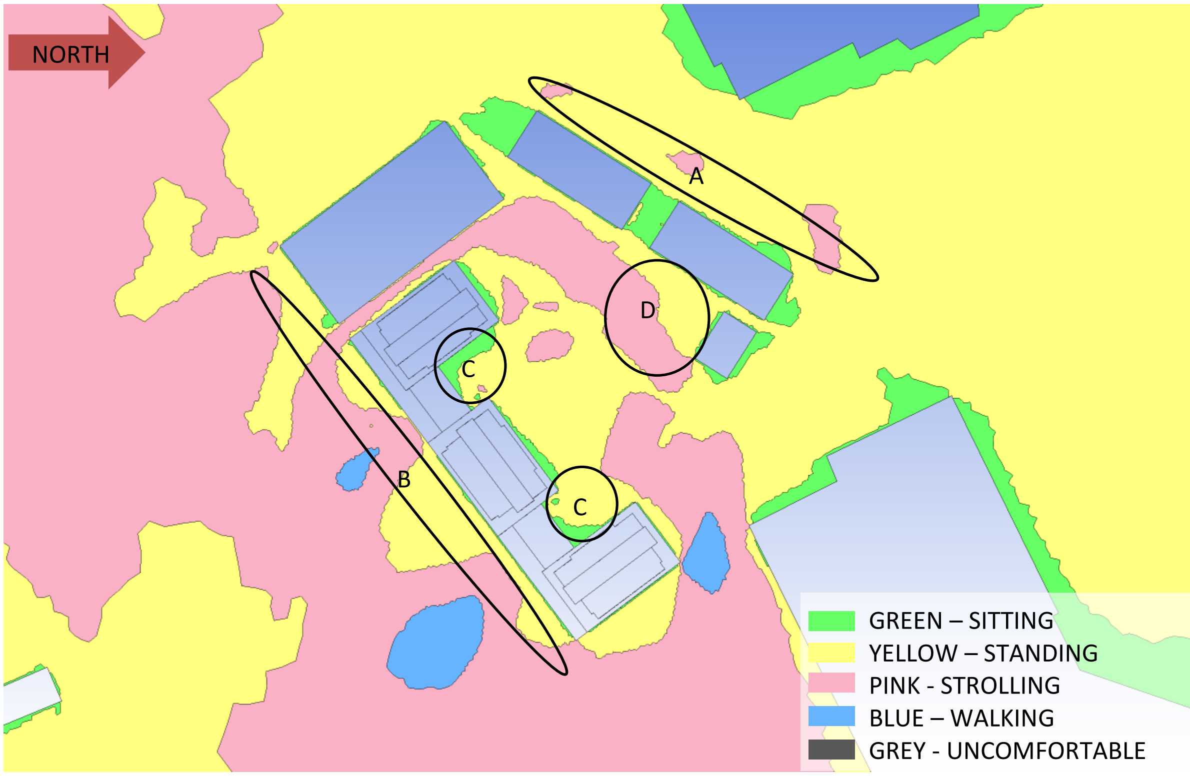


FIGURE 3A: SPRING – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS FULL SITE BUILD-OUT

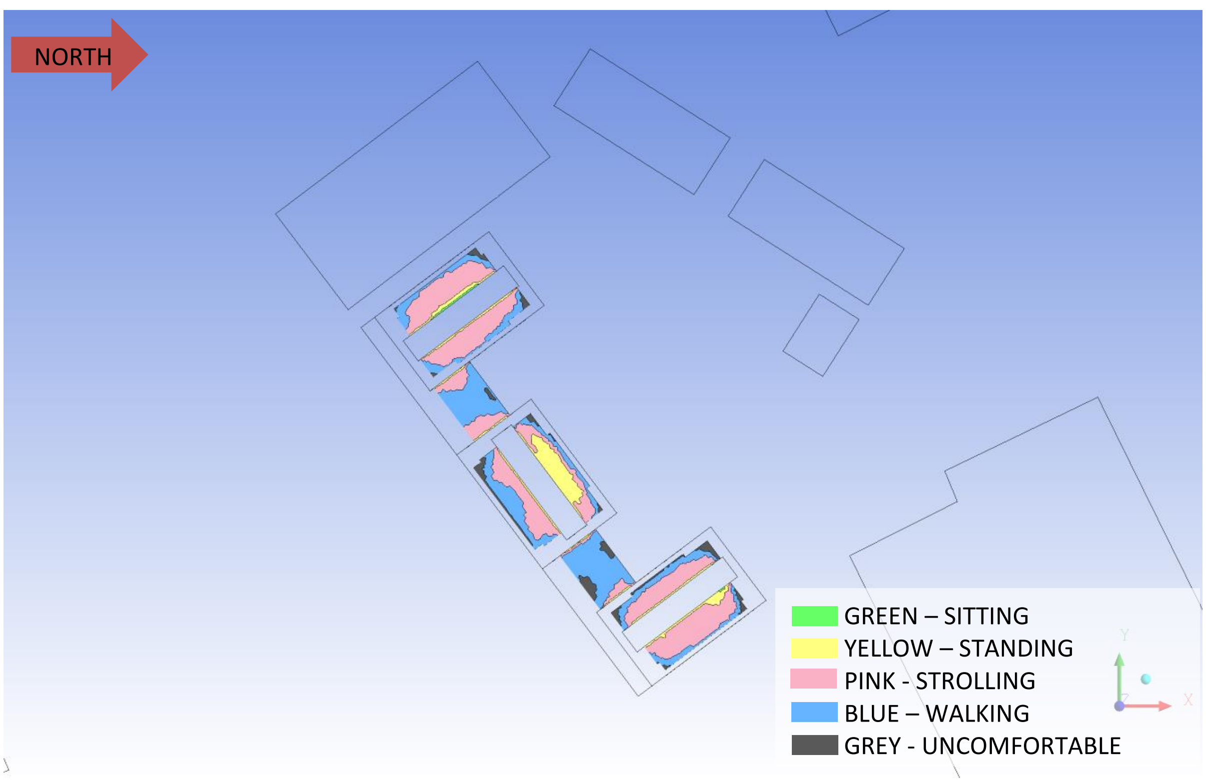


FIGURE 3B: SPRING – ELEVATED TERRACE PEDESTRIAN WIND CONDITIONS FULL SITE BUILD-OUT

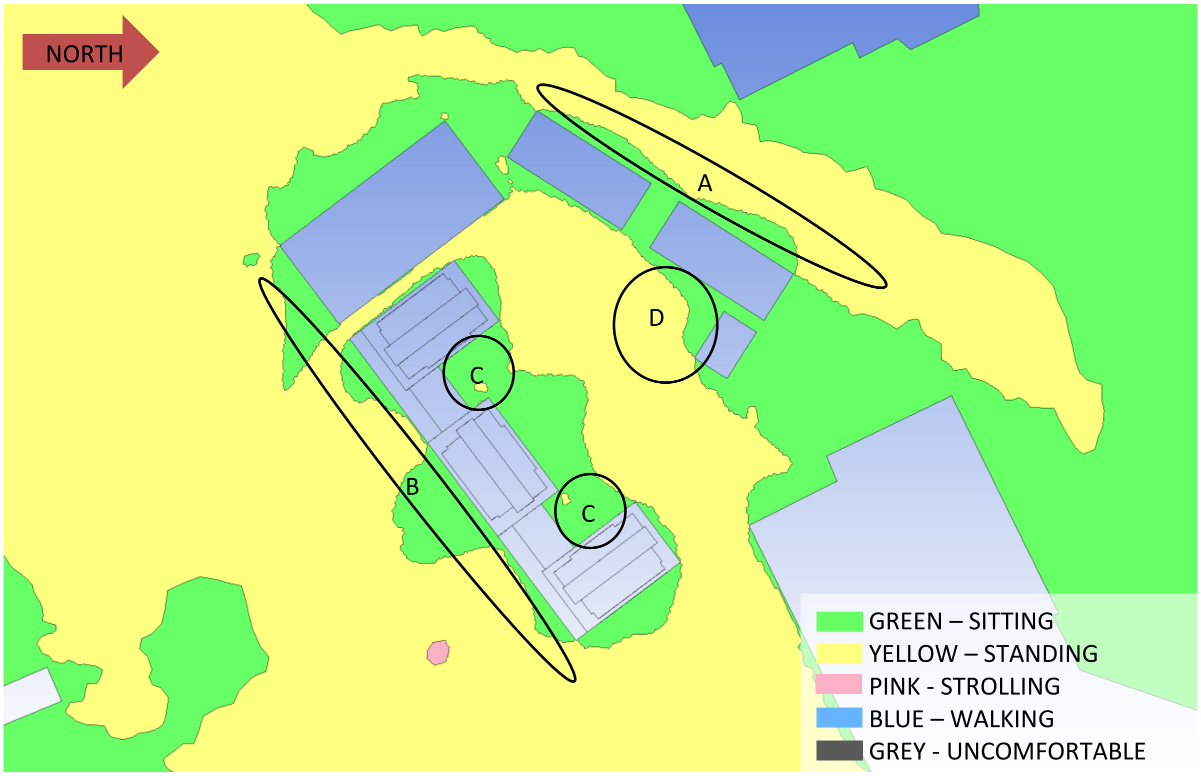


FIGURE 4A: SUMMER – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS FULL SITE BUILD-OUT

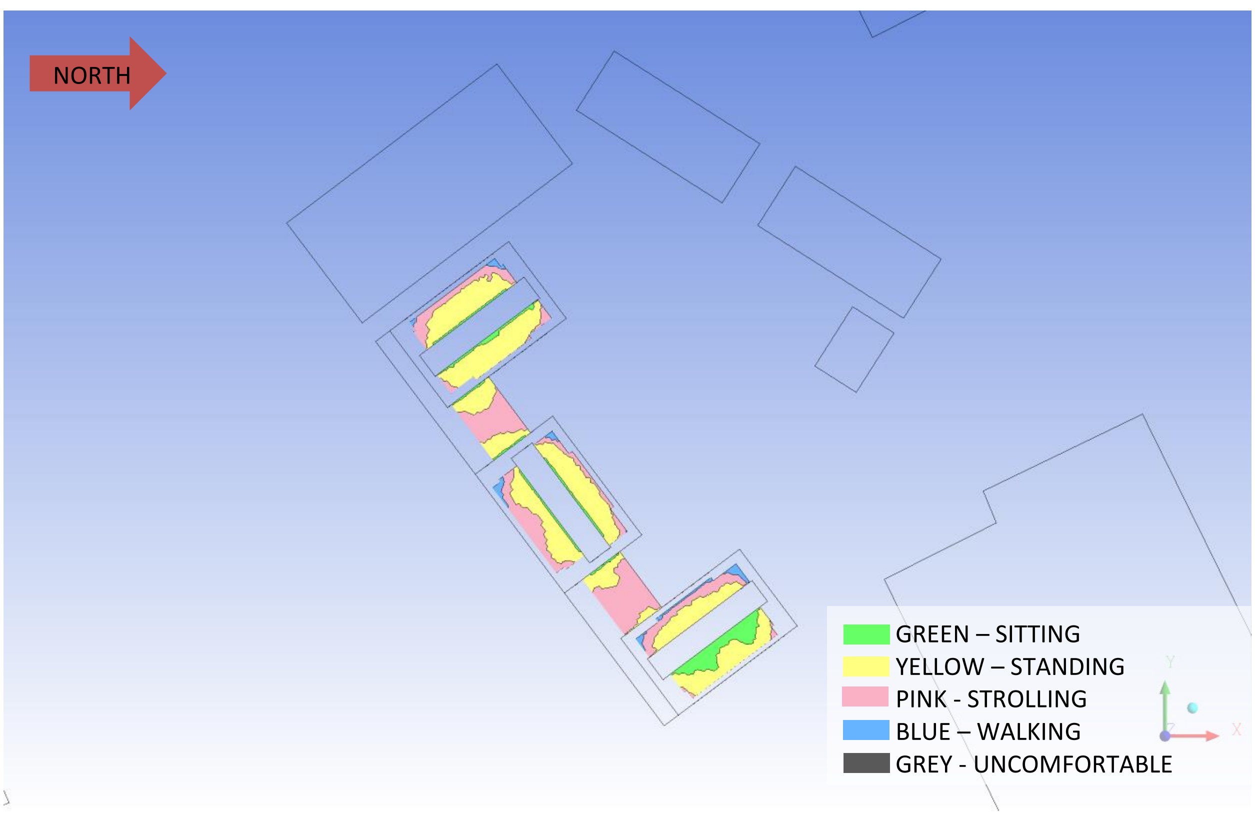


FIGURE 4B: SUMMER – ELEVATED TERRACE PEDESTRIAN WIND CONDITIONS FULL SITE BUILD-OUT

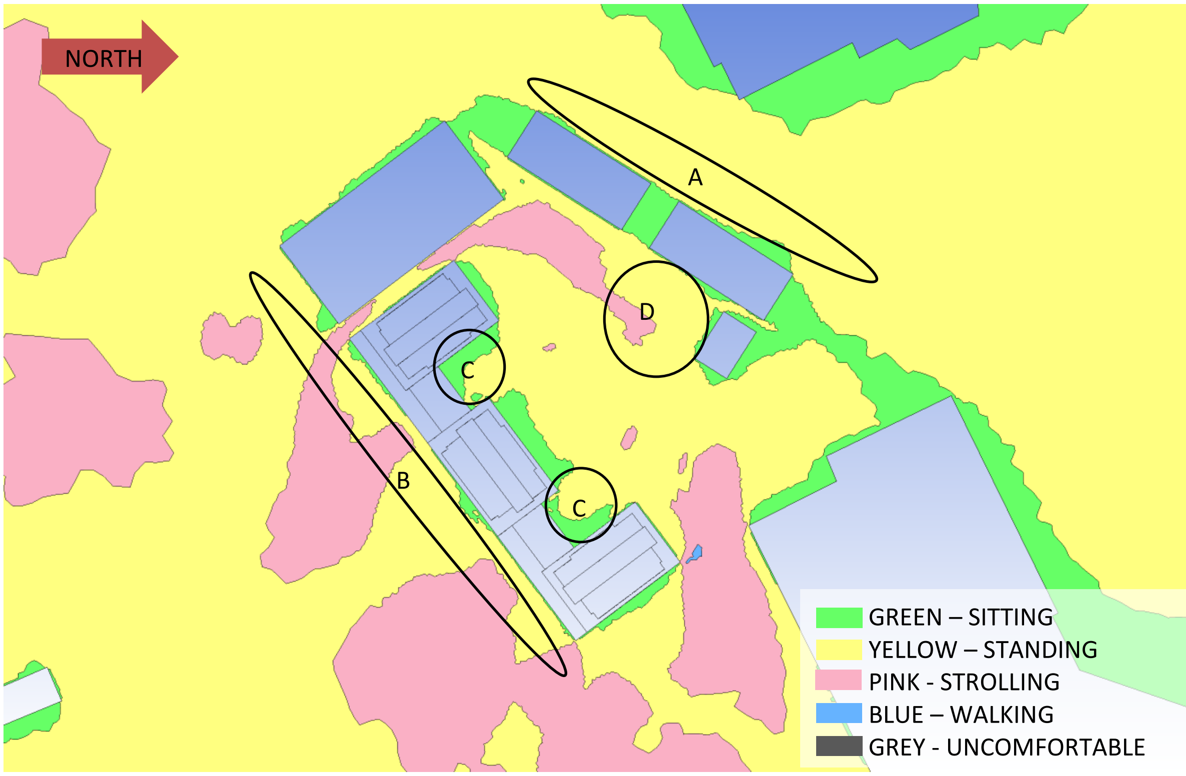


FIGURE 5A: AUTUMN – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS FULL SITE BUILD-OUT

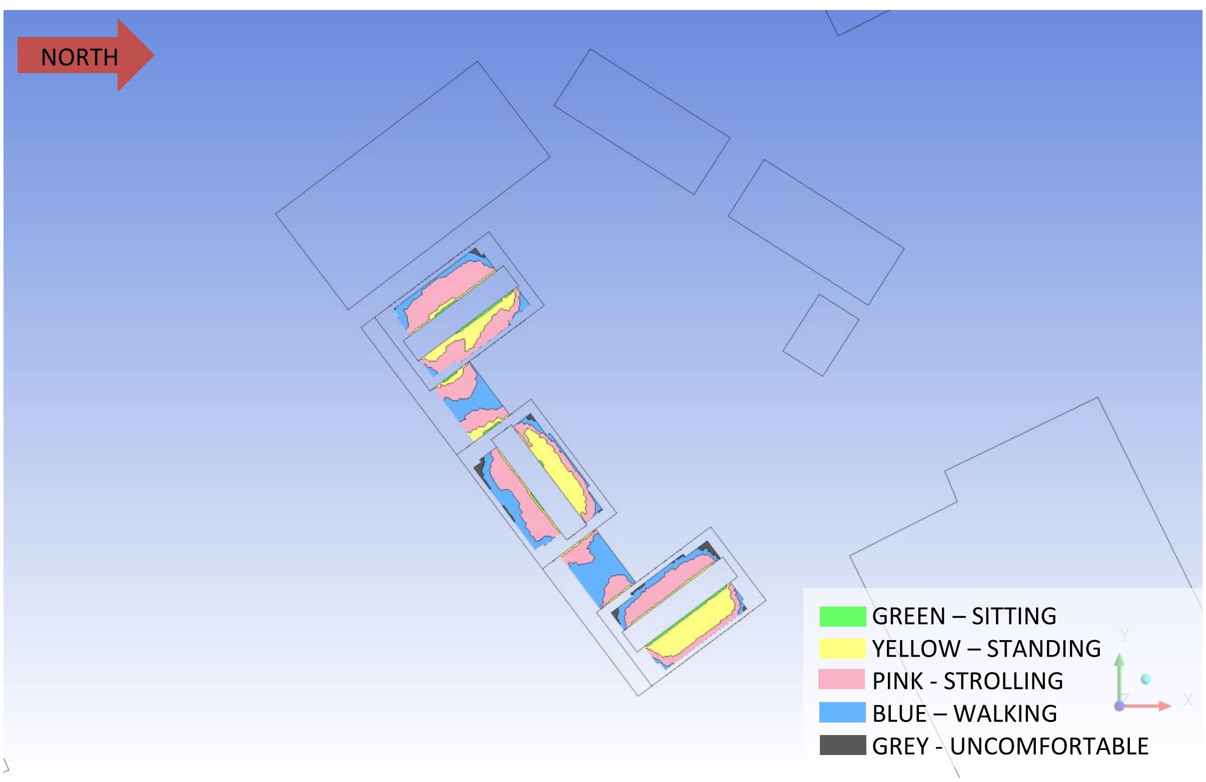


FIGURE 5B: AUTUMN – ELEVATED TERRACE PEDESTRIAN WIND CONDITIONS FULL SITE BUILD-OUT

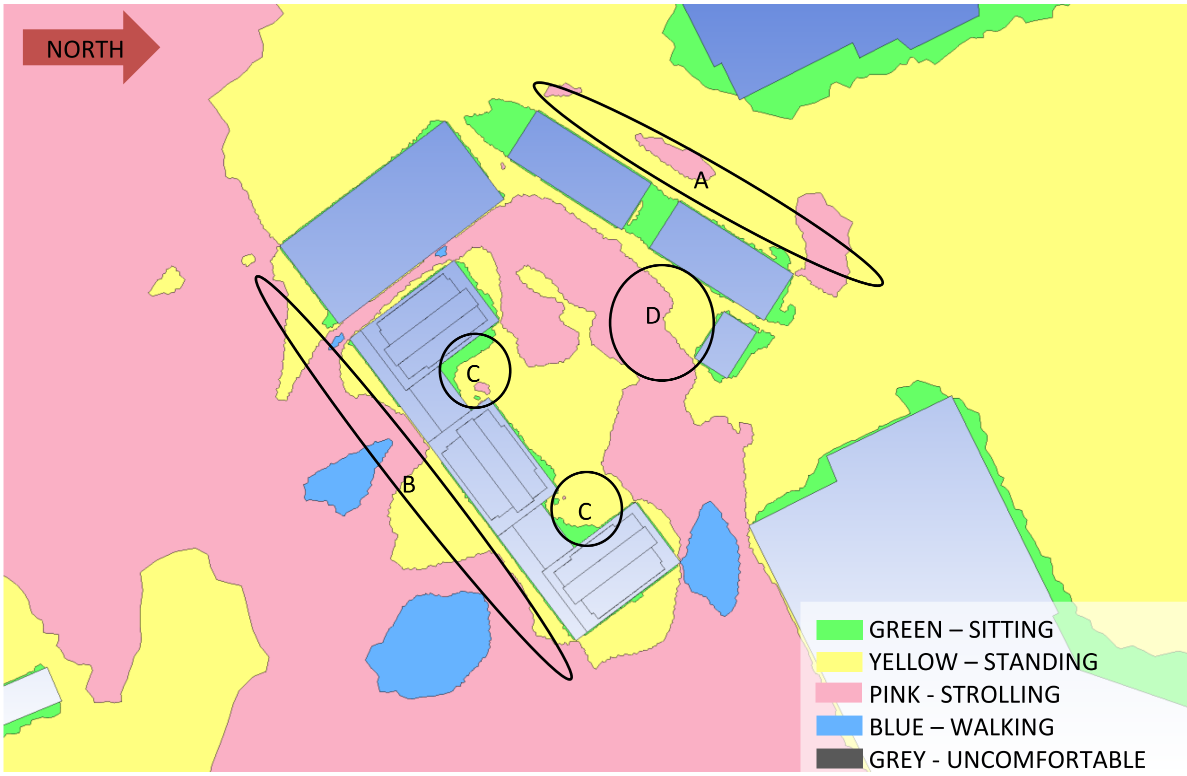


FIGURE 6A: WINTER – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS FULL SITE BUILD-OUT

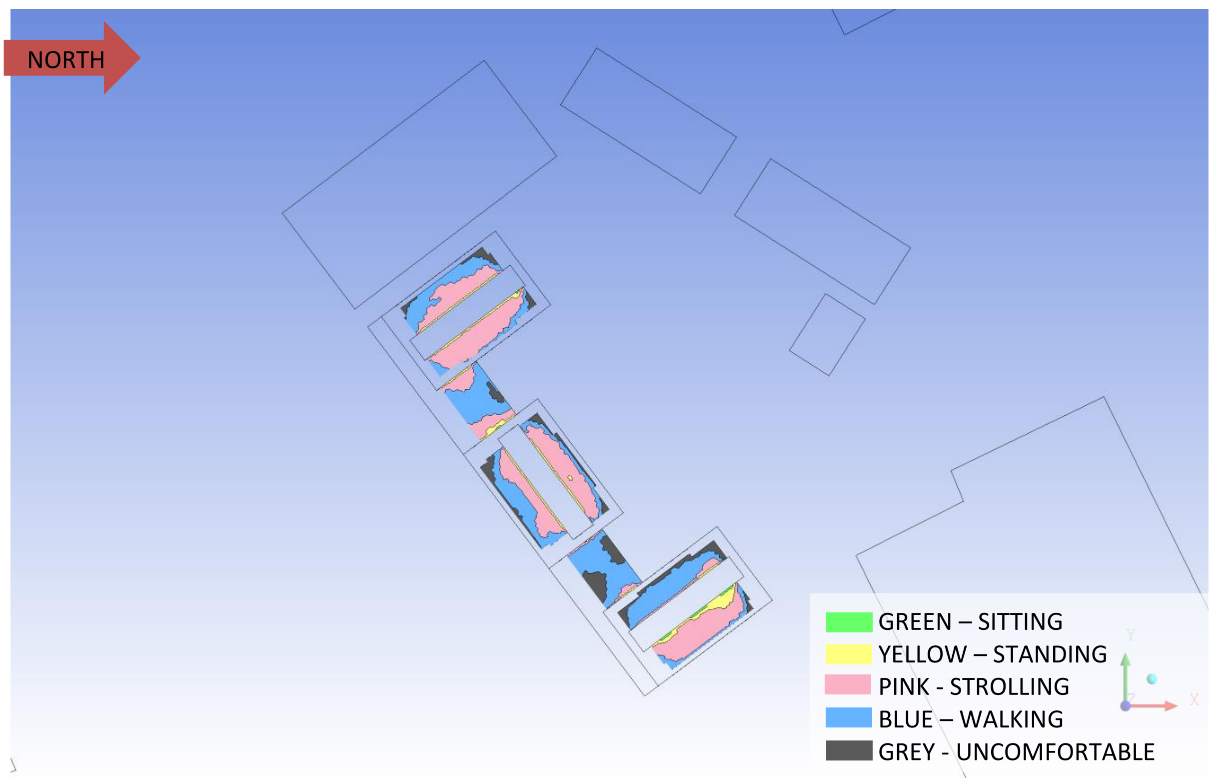


FIGURE 6B: WINTER – ELEVATED TERRACE PEDESTRIAN WIND CONDITIONS FULL SITE BUILD-OUT

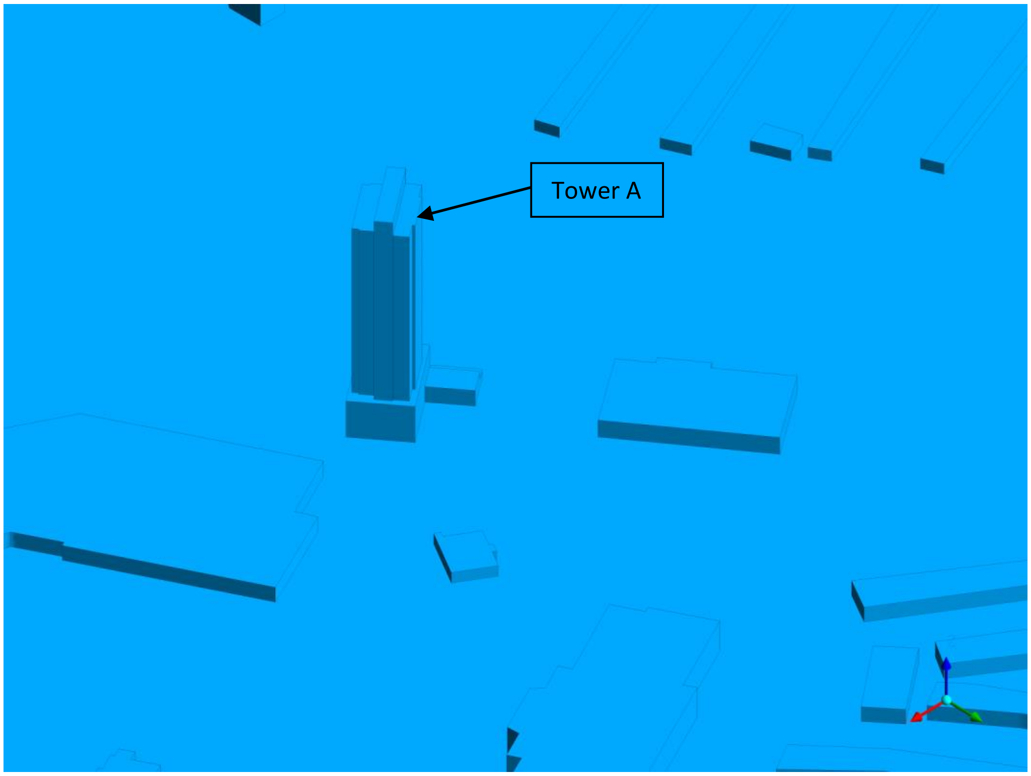


FIGURE 7A: COMPUTATIONAL MODEL PHASE 1, NORTHWEST PERSPECTIVE

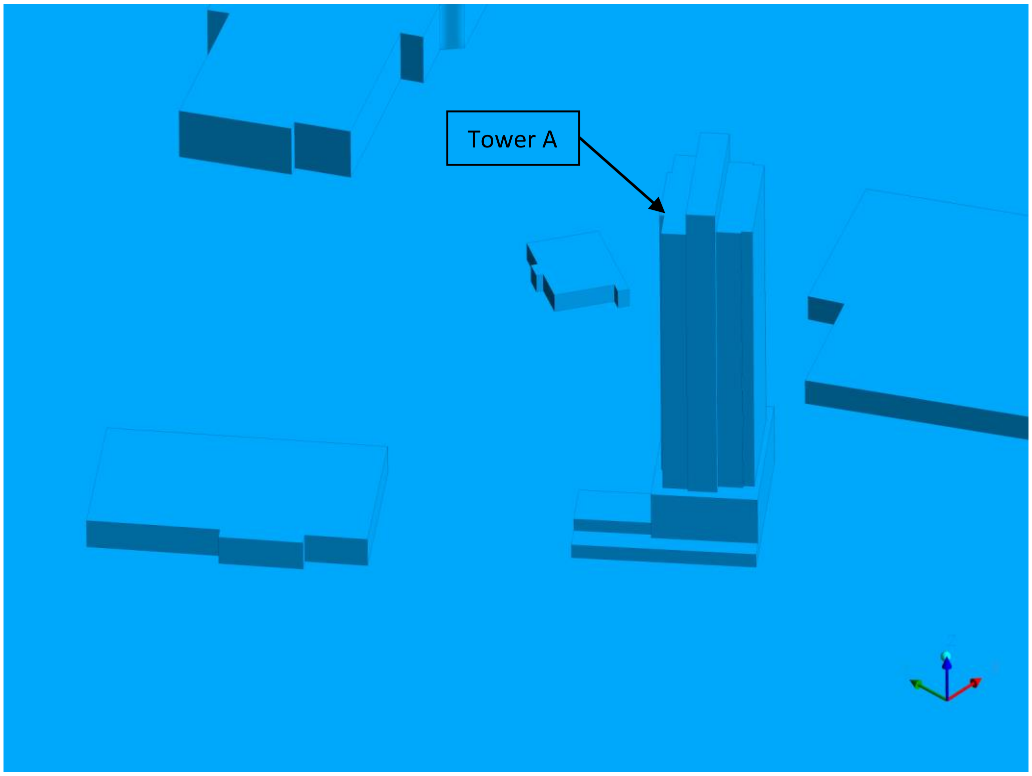


FIGURE 7B: COMPUTATIONAL MODEL PHASE 1, SOUTHEAST PERSPECTIVE

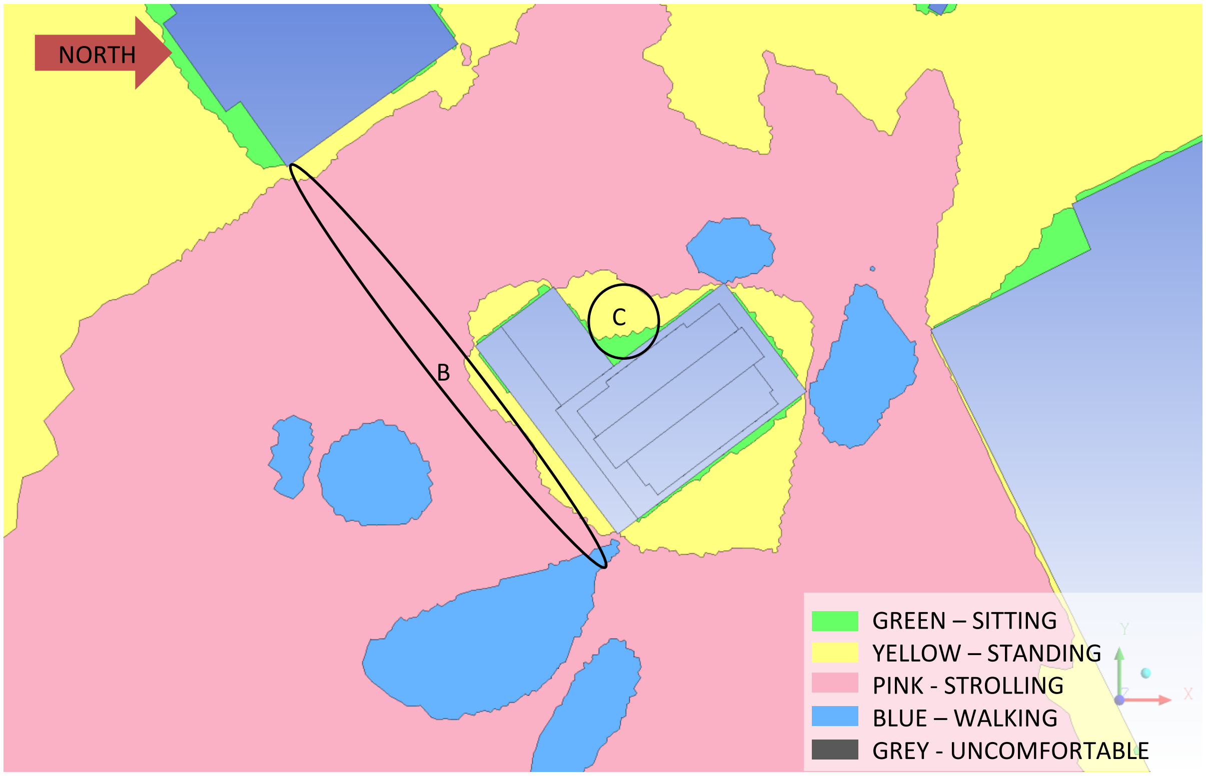


FIGURE 8A: SPRING – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS PHASE 1

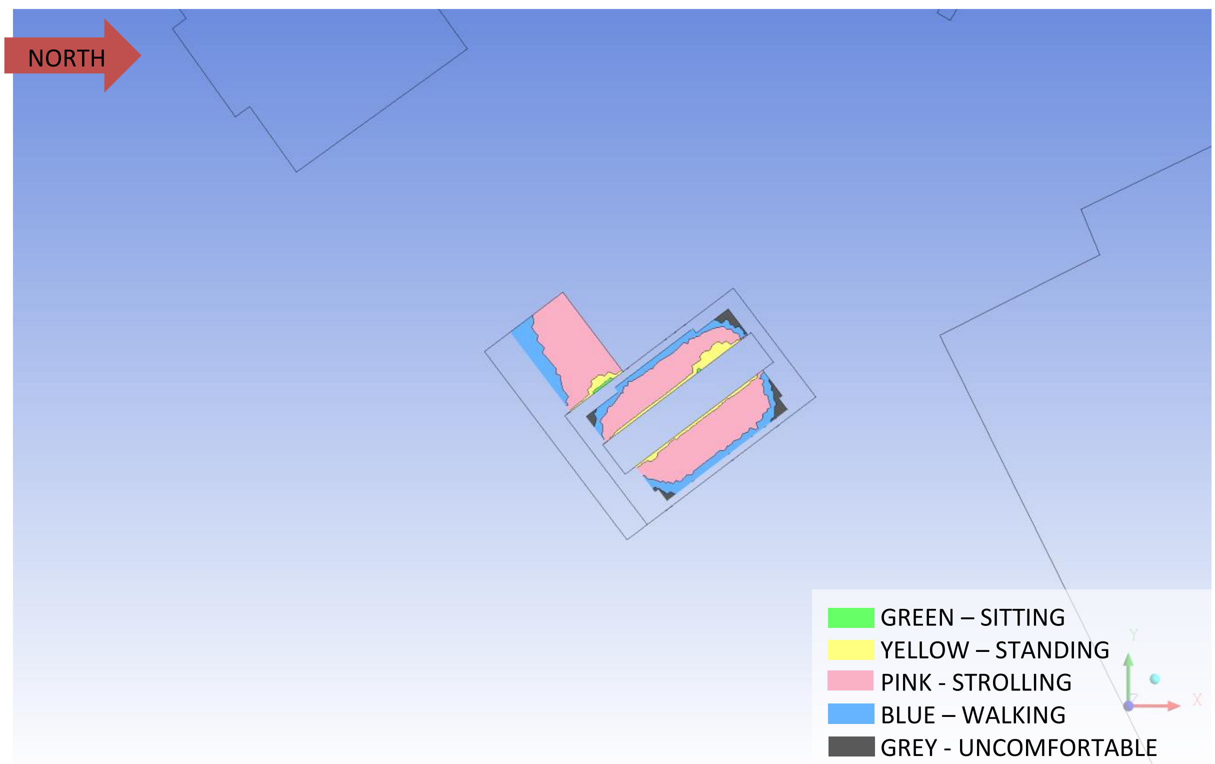


FIGURE 8B: SPRING – ELEVATED TERRACE PEDESTRIAN WIND CONDITIONS PHASE 1

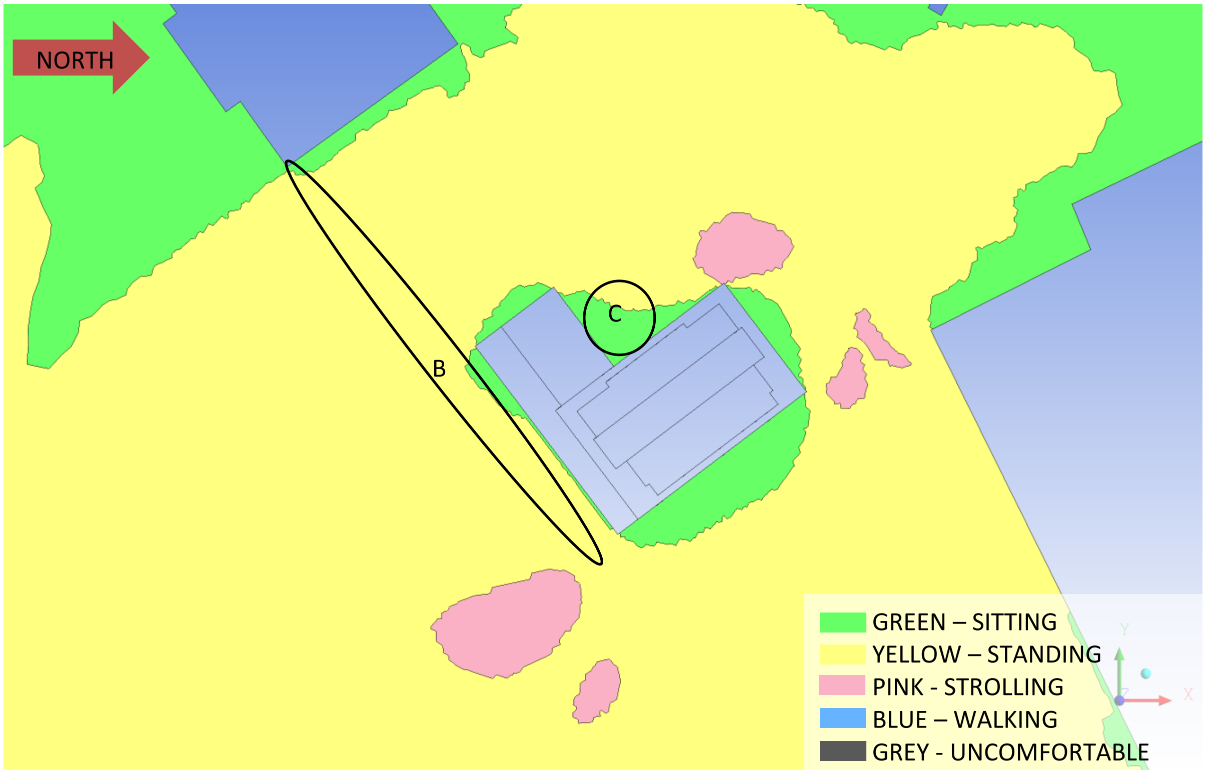


FIGURE 9A: SUMMER – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS PHASE 1

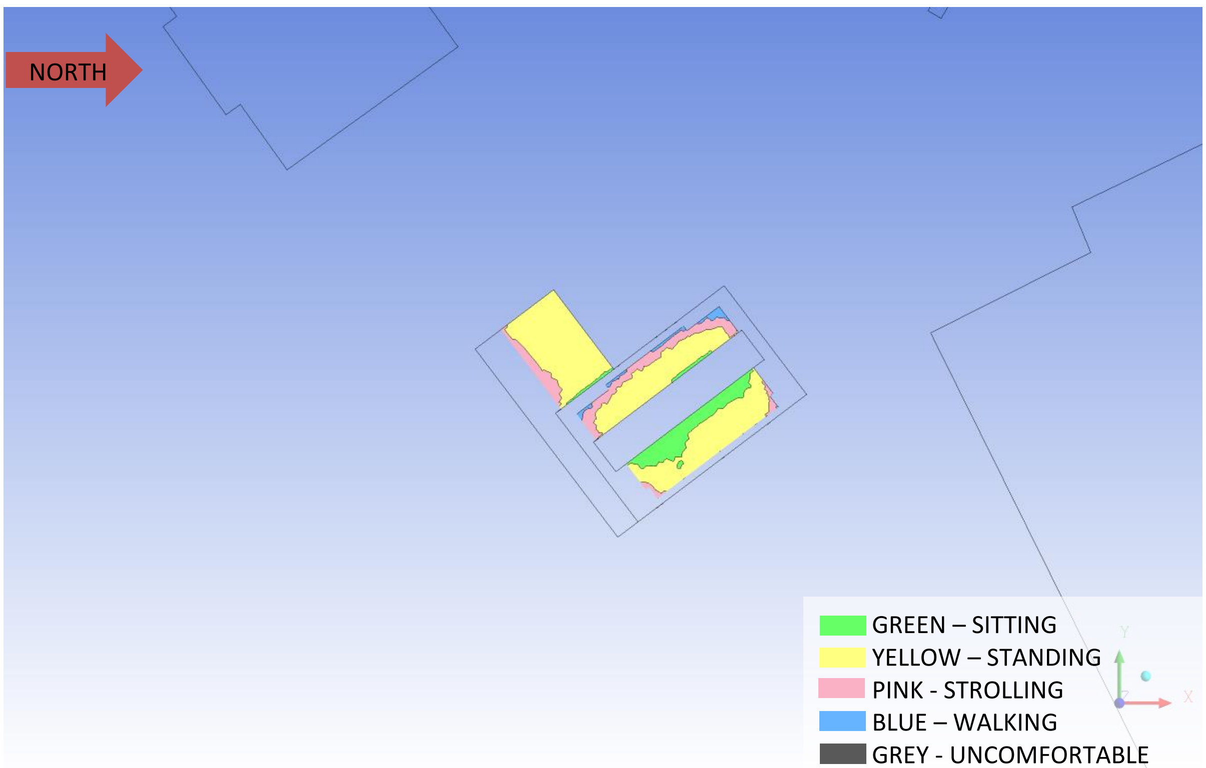


FIGURE 9B: SUMMER – ELEVATED TERRACE PEDESTRIAN WIND CONDITIONS PHASE 1

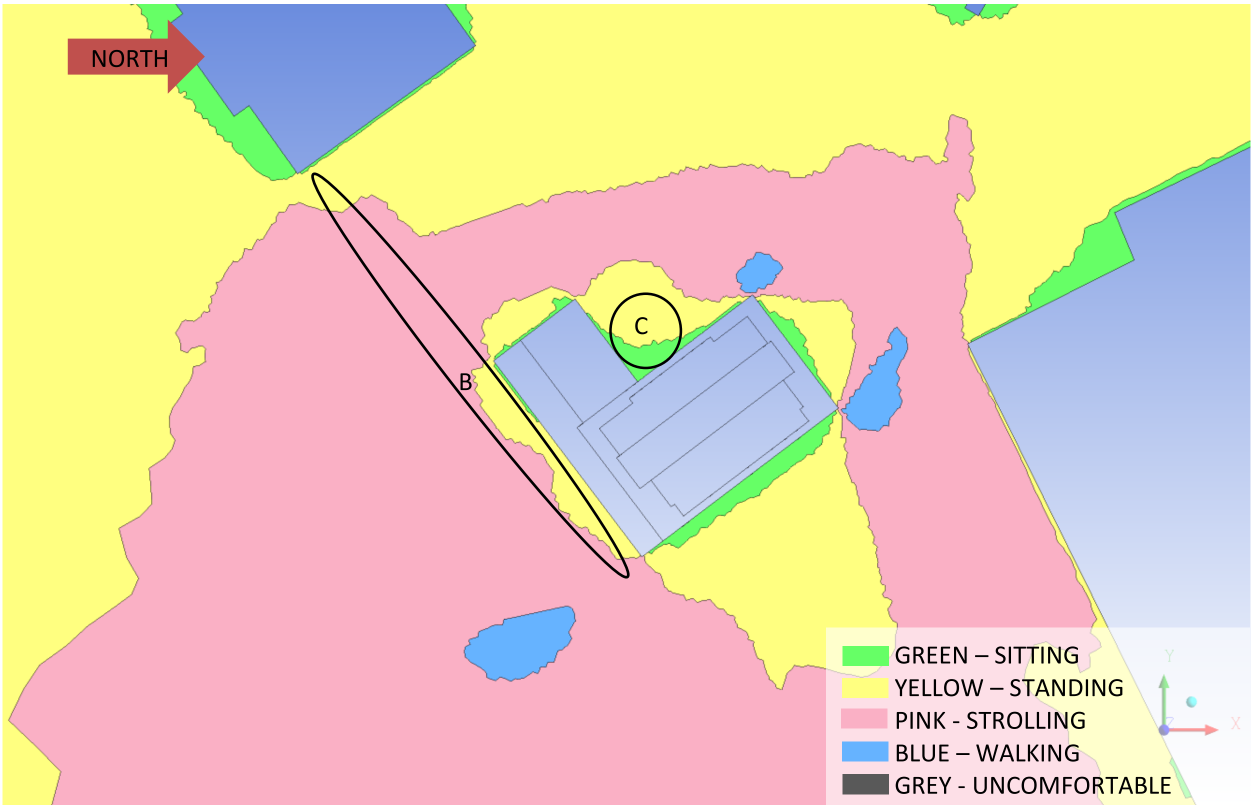


FIGURE 10A: AUTUMN – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS PHASE 1

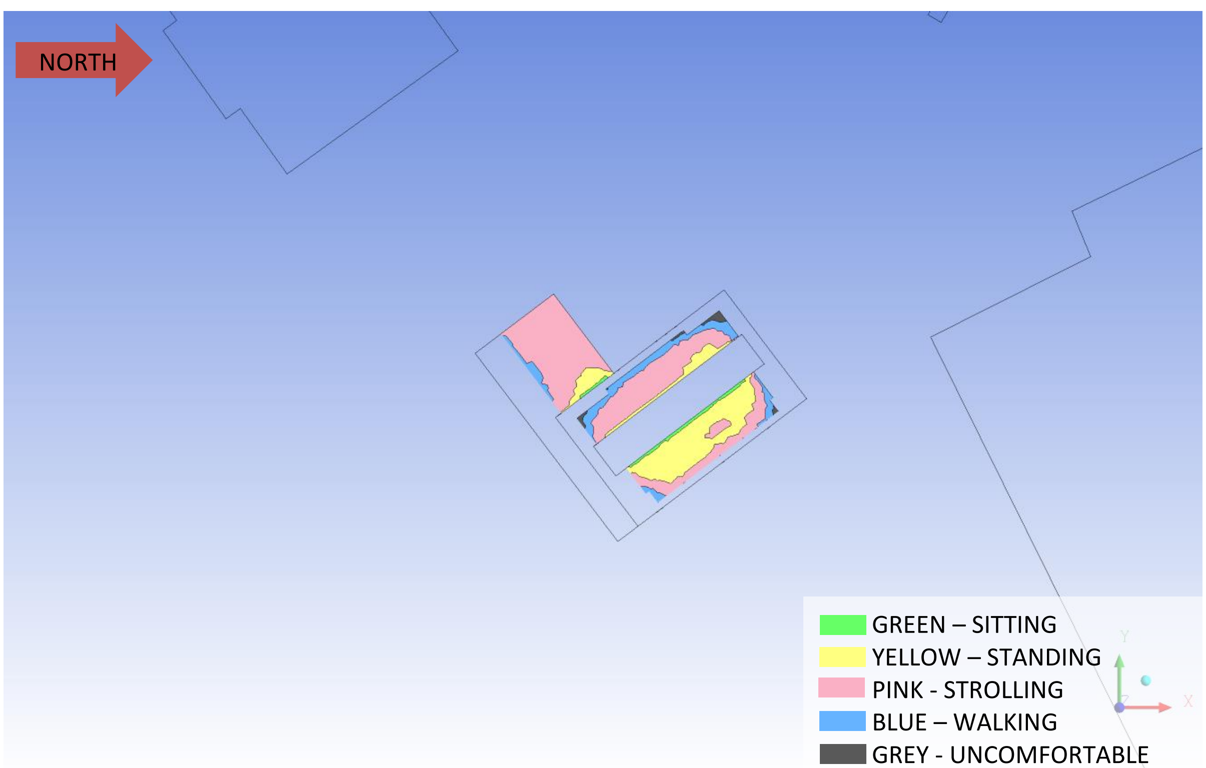


FIGURE 10B: AUTUMN – ELEVATED TERRACE PEDESTRIAN WIND CONDITIONS PHASE 1

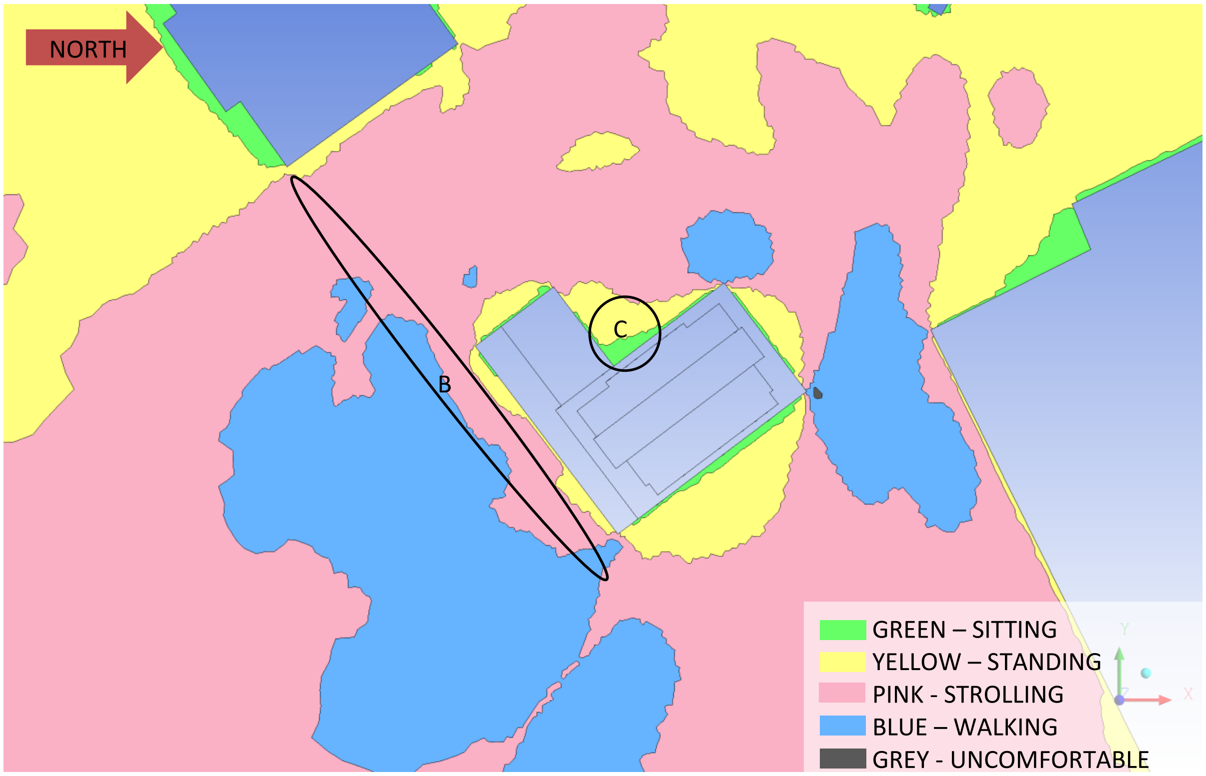


FIGURE 11A: WINTER – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS PHASE 1

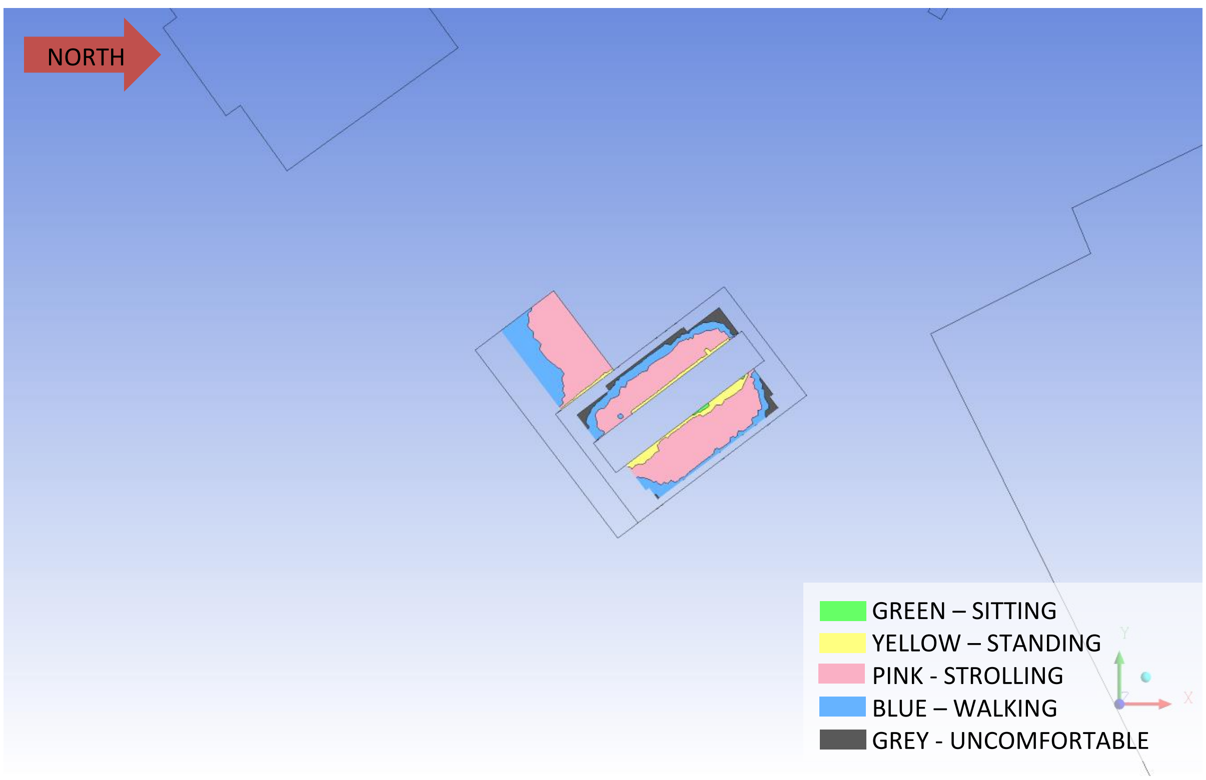


FIGURE 11B: WINTER – ELEVATED TERRACE PEDESTRIAN WIND CONDITIONS PHASE 1

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 AND CFD 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 behavior 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, ***Ug*** = gradient wind speed, ***Z*** = height above ground, ***Zg*** = 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 meter. 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.

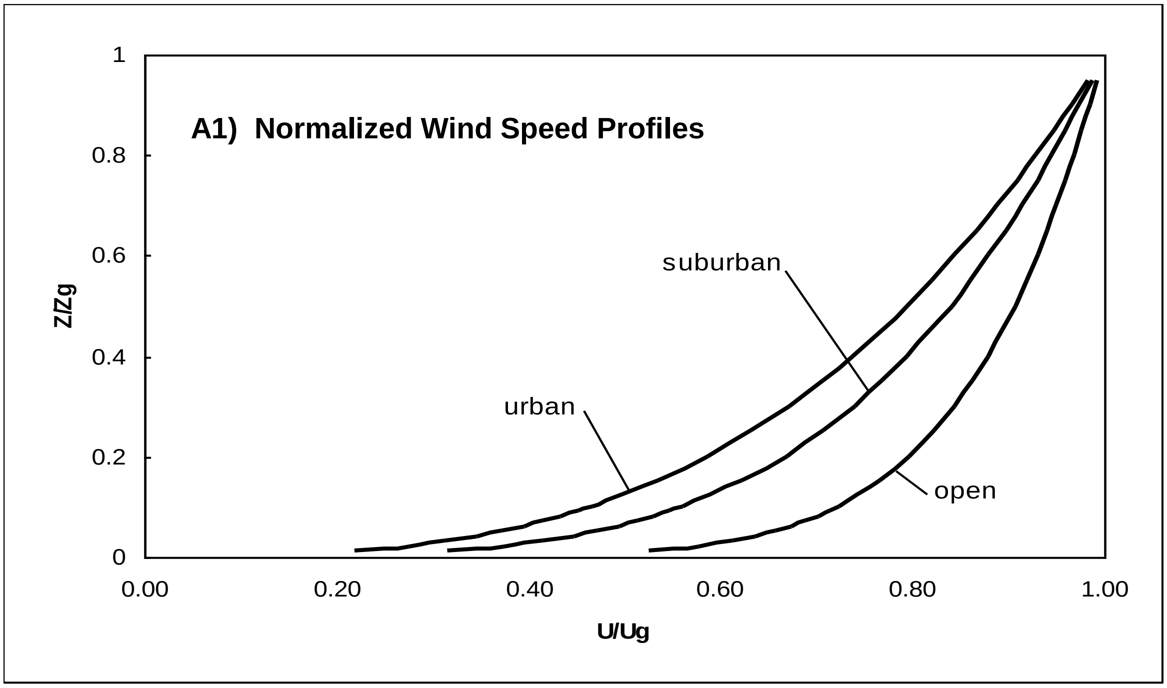
References

1. Teunissen, H.W., '*Characteristics Of The Mean Wind And Turbulence In The Planetary Boundary Layer*', Institute For Aerospace Studies, University Of Toronto, UTIAS # 32, Oct. 1970

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

4. Bradley, E.F., Coppin, P.A., Katen, P.C., '*Turbulent Wind Structure Above Very Rugged Terrain*', 9th Australian Fluid Mechanics Conference, Auckland, Dec. 1966



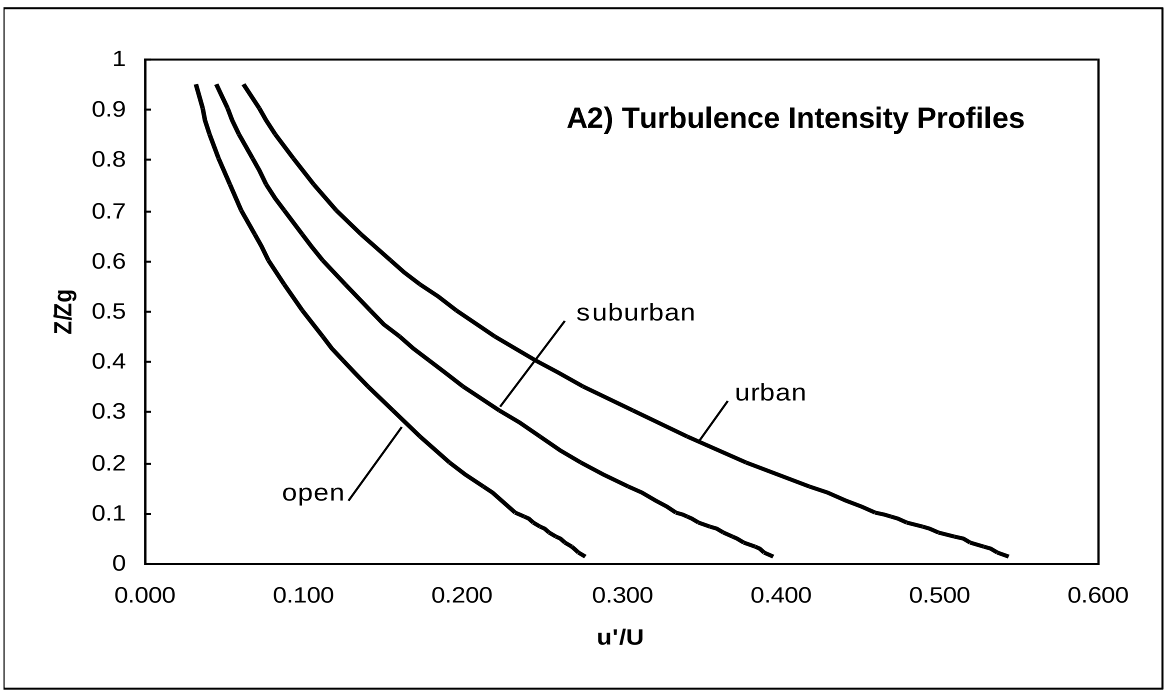


Figure A1 (Top): Mean Wind Speed Profiles
Figure A2 (Bottom): Turbulence Intensity Profiles (u' = fluctuation of mean velocity)

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 (> Ug) is the probability, fraction of time, that the gradient wind speed ***Ug*** 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:

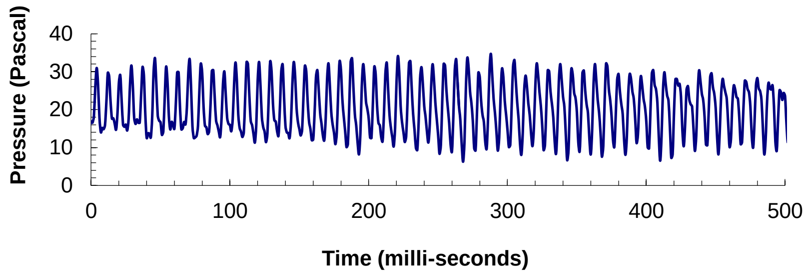
$$P_N(>20) = \Sigma_\theta P\left[\frac{(>20)}{\left(\frac{U_N}{U_g}\right)}\right]$$

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

Where, U_N/Ug 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



References

1. Davenport, A.G., '*The Dependence of Wind Loading on Meteorological Parameters*', Proc. of Int. Res. Seminar, Wind Effects On Buildings & Structures, NRC, Ottawa, 1967, University of Toronto Press.

2. Wu, S., Bose, N., 'An *extended power law model for the calibration of hot-wire/hot-film constant temperature probes*', Int. J. of Heat Mass Transfer, Vol.17, No.3, pp.437-442, Pergamon Press.