

**PEDESTRIAN LEVEL  
WIND STUDY**

2430 St. Paul Avenue  
Niagara Falls, Ontario

REPORT: GW23-238-WTPLW



January 24, 2024

PREPARED FOR

**ACK Architects Studio Inc.**

290 Glendale Avenue  
St. Catharines, Ontario  
L2T 2L3

PREPARED BY

Cristiano Kondo, MEng., Junior Wind Scientist  
Angelina Gomes, B.Eng., EIT, Wind Scientist  
Nick Petersen, P.Eng., Wind Engineer

## EXECUTIVE SUMMARY

This report describes a wind tunnel pedestrian level wind study undertaken to assess wind conditions for a proposed residential development located at 2430 St. Paul Avenue in Niagara Falls, Ontario. Two configurations were studied: (i) *existing scenario*, including all approved, surrounding developments and without the proposed development, and (ii) *proposed scenario* with the proposed development in place. The study involves wind tunnel measurements of pedestrian wind speeds using a physical scale model, combined with meteorological data integration, to assess pedestrian comfort at key areas within and surrounding the study site. Grade-level areas investigated include sidewalks, walkways, laneways, parking areas, the Eagle Valley Golf Course, and building access points. Wind comfort is also evaluated over the Level 15 and rooftop outdoor amenity terraces. 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 industry standard wind tunnel testing and data analysis procedures, architectural drawings provided by ACK Architects Studio Inc. in November 2023, surrounding street layouts, as well as existing and approved future building massing information obtained from the City of Niagara Falls, and recent site imagery.

A complete summary of the predicted wind conditions is provided in Section 5 of this report and is also illustrated in Figures 2A through 4B, as well as Tables A1-A2 and B1-B3 in the appendices. Based on wind tunnel test results, meteorological data analysis, and experience with similar developments in Niagara Falls, we conclude that the future wind conditions over most grade-level pedestrian wind-sensitive areas within and surrounding the study site will be acceptable for the intended uses on a seasonal basis. Exceptions include isolated secondary building access points and adjacent pedestrian areas at Level P1, for which mitigation is recommended as detailed in Section 5.2. Additionally, the Tower B Level 15 and rooftop outdoor amenity terraces will be suitable for sitting or more sedentary activities during the summer months, without the need for mitigation. To ensure that Tower A rooftop outdoor amenity terrace will be similarly calm, mitigation may be necessary, as described in Section 5.2.

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 conditions that could be considered unsafe.



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## 1. INTRODUCTION

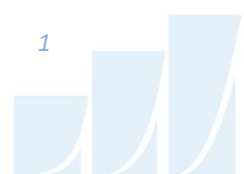
This report describes a wind tunnel pedestrian level wind (PLW) study undertaken to assess wind conditions for a proposed residential development located at 2430 St. Paul Avenue in Niagara Falls, Ontario. Two configurations were studied: (i) *existing scenario*, including all approved, surrounding developments and without the proposed development, and (ii) *proposed scenario* with the proposed development in place. The study was performed in accordance with industry standard wind tunnel testing techniques, architectural drawings provided by ACK Architects Studio Inc. in November 2023, surrounding street layouts and existing and approved future building massing information, as well as recent site imagery.

## 2. TERMS OF REFERENCE

The focus of this wind tunnel pedestrian wind study is the proposed development located at 2430 St. Paul Avenue in Niagara Falls, Ontario. The study site is located at the northeast corner of the intersection of St. Paul Avenue and Mountain Road.

The proposed development comprises two residential buildings forming an approximately “V”-shaped planform: the 15-storey Tower A to the west and the 19-storey Tower B to the southeast. A south driveway connecting St. Paul Avenue to the west and Mountain Road to the south provides access to residential lobbies, surface parking, and two levels of below-grade parking via a lower terrace parking garage access between the towers. Sloping topography over the site allows for residential units along the north elevations of Towers A and B at Parking Level P1. At the ground floor, each tower comprises a lobby and amenity space fronting the southern driveway with residential units elsewhere. The Tower A floorplate sets back from the west elevation at Levels 2, 10, and 12, accommodating private terraces. Similarly, the Tower B floorplate sets back from the southeast elevation at Levels 2, 12, and 15 accommodating private and outdoor amenity terraces. The tower floorplates set back at full height, where rooftop outdoor and indoor amenities, as well as mechanical spaces, complete each tower.

Regarding wind exposures, the near-field surroundings (defined as an area falling within a 200-metre (m) radius of the subject site) include open green space in all directions, with low-rise buildings to the south and northwest. The Eagle Valley Golf Club encompasses the northeast quadrant. The far-field



surroundings (defined as the area beyond the near field and within a 2-kilometre (km) radius) are characterized by low-rise buildings in all directions, with open green spaces from the northwest clockwise to the east, and the Sir Adam Beck Hydroelectric Station Reservoir approximately 1.3 kilometres to the northeast.

Grade-level areas investigated include sidewalks, walkways, laneways, parking areas, the Eagle Valley Golf Course, and building access points. Wind comfort is also evaluated over the Level 15 and rooftop outdoor amenity terraces. Figures 1A and 1B illustrate the *existing* and *proposed* study sites and surrounding context, respectively, and Photographs 1 through 6 depict the wind tunnel 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; (iii) recommend suitable mitigation measures, where required; and (iv) evaluate the influence of the proposed development on the existing wind conditions.

### **4. METHODOLOGY**

The approach followed to quantify pedestrian wind conditions over the site is based on wind tunnel measurements of wind speeds at selected locations on a reduced-scale physical model, meteorological analysis of the Niagara Region wind climate, and synthesis of wind tunnel data with industry-accepted guidelines<sup>1</sup>. The following sections describe the analysis procedures, including a discussion of the pedestrian comfort and safety guidelines.

#### **4.1 Wind Tunnel Context Modelling**

A detailed PLW study is performed to determine the influence of local winds at the pedestrian level for a proposed development. The physical model of the proposed development and relevant surroundings, illustrated in Photographs 1 through 6 following the main text, was constructed at a scale of 1:400. The

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<sup>1</sup> Niagara Region Pedestrian Level Wind Study Term of Reference Guide, July 2022



wind tunnel model includes all existing buildings and approved future developments within a full-scale diameter of approximately 840 metres. The general concept and approach to wind tunnel modelling is to provide building and topographic detail in the immediate vicinity of the study site on the surrounding model, and to rely on a length of wind tunnel upwind of the model to develop wind properties consistent with known turbulent intensity profiles that represent the surrounding terrain.

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 an 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 study was performed by testing a total of 76 sensor locations on the scale model in Gradient Wind's wind tunnel. Of these 76 sensors, 69 were located at grade and the remaining seven sensors were located over the various elevated terraces. Wind speed measurements were performed for each of the 76 sensors for 36 wind directions at 10° intervals. Figures 1A and 1B illustrate the *existing* and *proposed* study sites and surrounding context, respectively, while sensor locations used to investigate wind conditions are illustrated in Figures 2A through 4B.

Mean and peak wind speed values for each location and wind direction were calculated from real-time pressure measurements, recorded at a sample rate of 500 samples per second, and taken over a 60-second time period. This period at model-scale corresponds approximately to one hour in full-scale, which matches the time frame of full-scale meteorological observations. Measured mean and gust wind speeds at grade were referenced to the wind speed measured near the ceiling of the wind tunnel to generate mean and peak wind speed ratios. Ceiling height in the wind tunnel represents the depth of the boundary layer of wind flowing over the earth's surface, referred to as the gradient height. Within this boundary layer, mean wind speed increases up to the gradient height and remains constant thereafter. Appendices C and D provide greater detail of the theory behind wind speed measurements. Wind tunnel measurements for this project, conducted in Gradient Wind's wind tunnel facility, meet or exceed guidelines found in the National Building Code of Canada 2015 and of 'Wind Tunnel Studies of Buildings and Structures', ASCE Manual 7 Reports on Engineering Practice No 67.

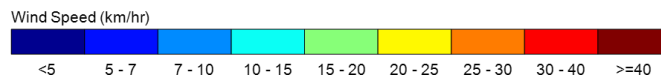
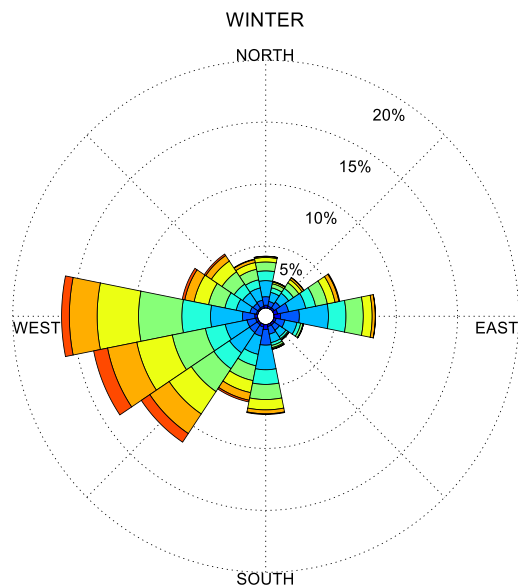
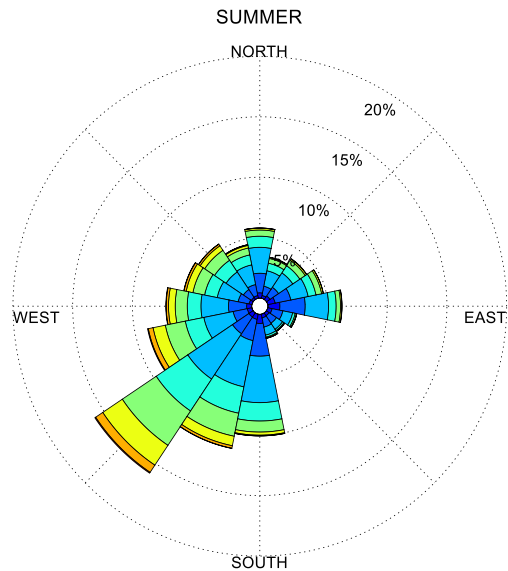


### 4.3 Meteorological Data Analysis

A statistical model for winds in Niagara Falls was developed from approximately 48-years of hourly meteorological wind data recorded at Niagara Falls International Airport and obtained from Environment and Climate Change Canada. Wind speed and direction data were divided into two distinct seasons, as stipulated in the noted Niagara Region Terms of Reference Guide<sup>1</sup>. More specifically, the summer season is defined as May through October, while the winter season is defined as November through April, inclusive.

The statistical model of the Niagara Falls area wind climate, which indicates the directional character of local winds on a seasonal basis, is illustrated on the following page. The plots illustrate seasonal distribution of measured wind speeds and directions in kilometers per hour (km/h). Probabilities of occurrence of different wind speeds are represented as stacked polar bars in sixteen azimuth divisions. The radial direction represents the percentage of time for various wind speed ranges per wind direction during the measurement period. The preferred wind speeds and directions can be identified by the longer length of the bars. For Niagara Falls, the most common winds concerning pedestrian comfort occur from the south clockwise to the northwest, and to a lesser extent from the northeast quadrant. The most common winds during the summer season occur for easterly wind directions. 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. Also, 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 NIAGARA FALLS INTERNATIONAL AIRPORT, NIAGARA FALLS, NEW YORK



### Notes:

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



#### 4.4 Pedestrian Comfort and Safety Guidelines

Pedestrian comfort and safety guidelines are based on the mechanical effects of wind without consideration of other meteorological conditions (i.e. temperature, relative humidity). The comfort guidelines assume that pedestrians are appropriately dressed for a specified outdoor activity during any given season. Since both mean and gust wind speeds affect pedestrian comfort, their combined effect is defined in the Niagara Region Terms of Reference<sup>1</sup>. More specifically, the criteria are defined as a Gust Equivalent Mean (GEM) wind speed, which is the greater of the mean wind speed or the gust wind speed divided by 1.85.

Four pedestrian comfort classes and corresponding GEM wind speed ranges are used to assess pedestrian comfort, which include: (i) Sitting; (ii) Standing; (iii) Walking; and (iv) Uncomfortable. More specifically, the comfort classes, wind speed ranges, and limiting criteria are summarized as follows:

- (i) **Sitting** – GEM wind speeds below 10 km/h occurring more than 80% of the time would be considered acceptable for sedentary activities, including sitting.
- (ii) **Standing** – GEM wind speeds below 15 km/h (i.e. 10-15 km/h) occurring more than 80% of the time are acceptable for activities such as standing, strolling or more vigorous activities.
- (iii) **Walking** – GEM wind speeds below 20 km/h (i.e. 15-20 km/h) occurring more than 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% criterion for walking. Brisk walking and exercise, such as jogging, would be acceptable for moderate excesses of this criterion.

Gust wind speeds greater than 90 km/h, occurring more than 0.1% of the time on an annual basis, 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 a vulnerable member of the population to fall.

Experience and research on people's perception of mechanical wind effects have shown that if the wind speed levels are exceeded more than 20% of the time, the activity level would be judged to be

uncomfortable by most people. For instance, if GEM wind speeds of 10 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 GEM wind speeds of 20 km/h at a location were exceeded for more than 20% of the time, walking or less vigorous activities would be considered uncomfortable. As most of these criteria are based on subjective reactions of a population to wind forces, their application is partly based on experience and judgment.

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

### **DESIRED PEDESTRIAN COMFORT CLASSES FOR VARIOUS LOCATION TYPES**

Location Types	Desired Comfort Classes
Primary Building Entrance	Standing
Secondary Building Access Point	Walking
Public Sidewalks / Pedestrian Walkways	Walking
Outdoor Amenity Spaces	Sitting / Standing
Cafés / Patios / Benches / Gardens	Sitting / Standing
Plazas	Standing / Walking
Transit Stops	Standing
Public Parks	Sitting / Walking
Garage / Service Entrances	Walking
Vehicular Drop-Off Zones	Walking
Laneways / Loading Zones	Walking

## **5. RESULTS AND DISCUSSION**

Tables A1 and A2 in Appendix A provide a summary of seasonal comfort predictions for each sensor location under the *existing* massing scenario. Similarly, Tables B1-B3 in Appendix B provide the seasonal

comfort predictions for under the *proposed* massing scenario. The tables indicate the 80% non-exceedance GEM wind speeds and corresponding comfort classifications as defined in Section 4.4. In other words, a wind speed threshold of 19.1 for the summer season indicates that 80% of the measured data falls at or below 19.1 km/h during the summer months and conditions are therefore suitable for walking, as the 80% threshold value falls within the exceedance range of 15-20 km/h for walking. The tables include the predicted threshold values for each sensor location during each season, accompanied by the corresponding predicted comfort class (i.e., sitting, standing, walking, etc.).

The most significant findings of the PLW study are summarized in Sections 5.1 and 5.2. To assist with understanding and interpretation, predicted conditions for the proposed development are also illustrated in colour-coded format in Figures 2A through 4B. Conditions suitable for sitting are represented by the colour blue, while standing is represented by green, and walking by yellow. Conditions considered uncomfortable for walking are represented by the colour orange. For locations where the wind safety criterion is exceeded, the sensor is highlighted in red.

### 5.1 Pedestrian Comfort Suitability – *Existing Scenario*

Based on the analysis of the measured data, consideration of local climate data, and the suitability descriptors provided in Tables A1 and A2 in Appendix A and illustrated in Figures 2A and 2B, this section summarizes the significant findings of the PLW study with respect to the *existing scenario*, as follows:

1. Most public sidewalks, walkways, laneways, and landscaped spaces within and surrounding the proposed development currently experience wind conditions suitable for walking or better throughout the year. Exceptions include areas along Mountain Road (Sensors 10, 12, & 17-21), and isolated areas along St. Paul Avenue (Sensors 3 & 36), which exceeds the walking criterion during the winter months. It is notable that all areas remain safe annually, as defined in Section 4.4.
2. Tested areas of Eagle Valley Golf Course directly north and east of the site (Sensors 37-48) are currently suitable for standing or better during the summer months and walking or better during the winter months.



3. 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.

## 5.2 Pedestrian Comfort Suitability – Proposed Scenario

Based on the analysis of the measured data, consideration of local climate data, and the suitability descriptors provided in Tables B1-B3 in Appendix B and illustrated in Figures 3A through 4B, this section summarizes the significant findings of the PLW study with respect to the *proposed scenario*, as follows:

1. Most public sidewalks, walkways, laneways, landscaped spaces, and parking areas within and surrounding the proposed development will experience wind conditions suitable for walking or better throughout the year, which is acceptable for the intended uses of spaces. Exceptions include isolated areas along St. Paul Avenue and Mountain Road, (Sensors 3 and 17-18, respectively), and several landscaped areas and walkways internal to the site (Sensors 23, 30, & 34), which exceed the walking criterion during the winter months. It is noteworthy that these wind conditions are largely pre-existing, remain safe annually, and exceedances of the walking threshold are generally marginal. Considering the limited expected pedestrian traffic during the winter months, mitigation is not considered necessary in these areas. Further, the significant existing plantings along Mountain Road and St. Paul Avenue not accounted for in the wind tunnel test, if retained, would buffer salient westerly winds approaching the site, further reducing wind speeds.
2. The primary building entrances (Sensors 51 & 54) will be comfortable for standing throughout the year, which is appropriate.

Most secondary building access points (including stairwell exits and vehicle entrances) throughout the proposed development will be comfortable for walking or better throughout the year, which is appropriate. Exceptions include an area at the P1 Level of Tower B near the southwest corner (Sensor 23), and the lower terrace providing parking garage access (Sensors 67 & 69), which exceed the walking criterion during the winter months. To ensure walking conditions at the noted areas throughout the year, it is recommended to install 2.0-metre-deep canopy or pergola structures overhead of the access points, along the northwest and southeast sides of

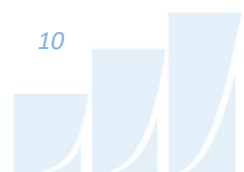


Tower B, which will also serve to improve conditions along the adjacent walkways. It is further recommended to raise the northeast perimeter guard of the lower terrace to 2.0 metres above the walking surface.

3. The proposed practice putting green to the north (Sensors 28-31) will be suitable for standing during the summer months, which is acceptable for the intended seasonal use of space.
4. Tested areas of Eagle Valley Golf Course directly north and east of the site (Sensors 37-48) will generally experience wind conditions suitable for standing or better during the summer, which is acceptable for the intended seasonal use of space and generally unchanged from pre-existing conditions.
5. The Tower B Level 15 and rooftop outdoor amenity terraces (Sensors 70-72) will be suitable for sitting or more sedentary activities during the summer months, without the need for mitigation.
6. The Tower A rooftop outdoor amenity terrace will experience a mix of sitting conditions central to the terrace (Sensors 74 & 75) and standing wind conditions towards the northwest (Sensor 76) and southeast (Sensor 73) corners. If sitting wind conditions are desired over the full terrace space, it is recommended to raise the terrace perimeter guards at the noted corners to at least 1.8 metres above the walking surface and/or provide targeted barriers directly southwest of seating areas within those areas. Barriers may take the form of dense coniferous plantings in raised planters, high-solidity wind screens, or a combination thereof, and should measure at least 1.6 metres tall at the time of installation.
7. 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. CONCLUSIONS AND RECOMMENDATIONS**

This report summarizes the methodology, results, and recommendations related to a pedestrian level wind study for a proposed residential development located at 2430 St. Paul Avenue in Niagara Falls, Ontario. The study was performed in accordance with industry standard wind tunnel testing and data analysis procedures.



A complete summary of the predicted wind conditions is provided in Section 5 of this report and is also illustrated in Figures 2A through 4B, as well as Tables A1-A2 and B1-B3 in the appendices. Based on wind tunnel test results, meteorological data analysis, and experience with similar developments in Niagara Falls, we conclude that the future wind conditions over most grade-level pedestrian wind-sensitive areas within and surrounding the study site will be acceptable for the intended uses on a seasonal basis. Exceptions include isolated secondary building access points and adjacent pedestrian areas at Level P1, for which mitigation is recommended as detailed in Section 5.2.

Additionally, the Tower B Level 15 and rooftop outdoor amenity terraces will be suitable for sitting or more sedentary activities during the summer months, without the need for mitigation. To ensure that Tower A rooftop outdoor amenity terrace will be similarly calm, mitigation may be necessary, as described in Section 5.2.

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 conditions that could be considered unsafe.

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

Sincerely,

***Gradient Wind Engineering Inc.***



Cristiano Kondo, MEng.,  
Junior Wind Scientist



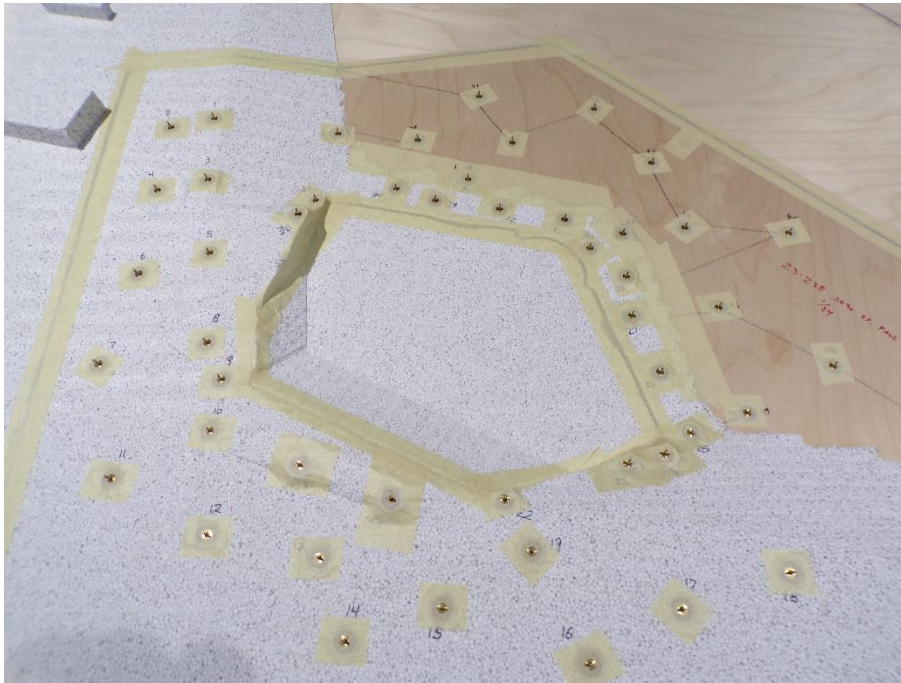
Nick Petersen, P.Eng.,  
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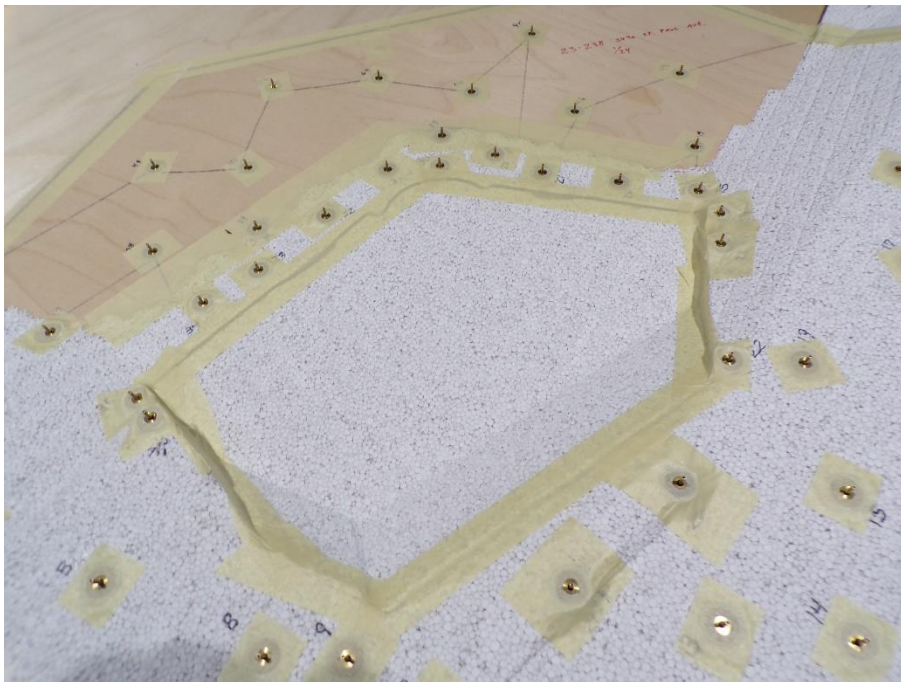
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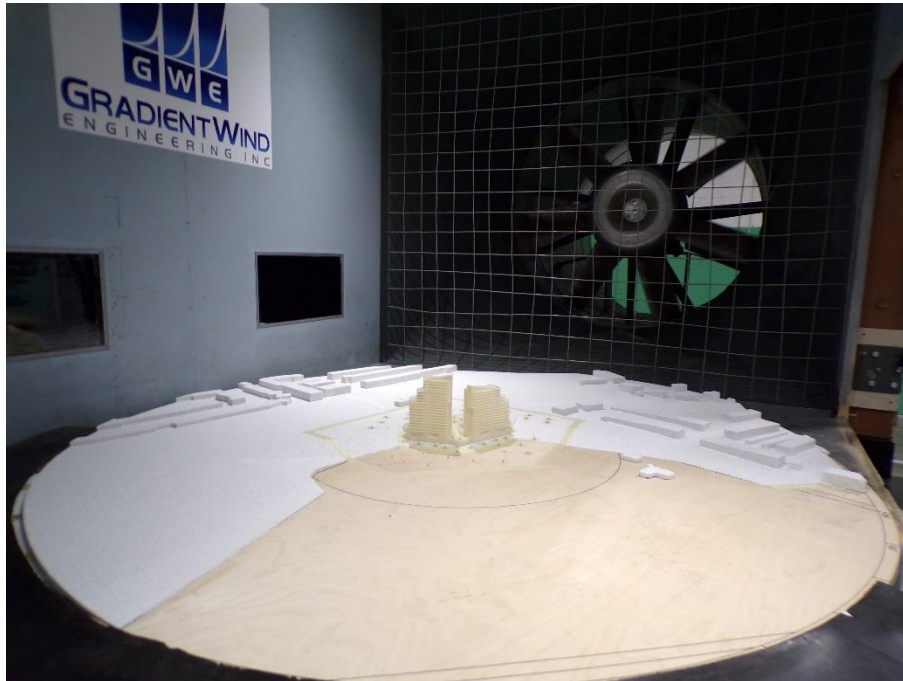


**PHOTOGRAPH 1: CLOSE-UP VIEW OF EXISTING CONTEXT MODEL LOOKING NORTHWEST**

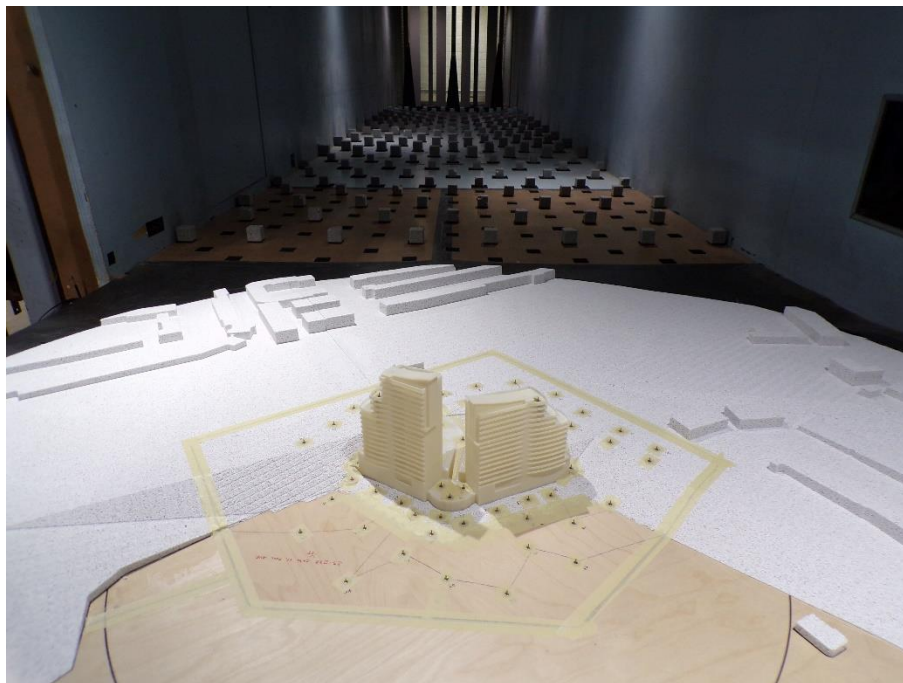


**PHOTOGRAPH 2: CLOSE-UP VIEW OF EXISTING CONTEXT MODEL LOOKING NORTHEAST**



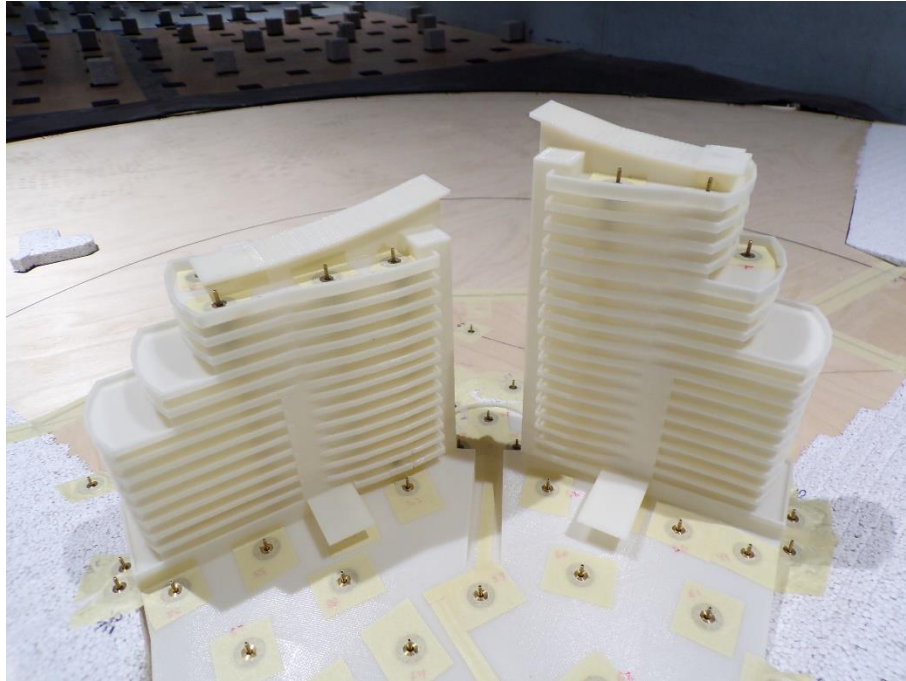


**PHOTOGRAPH 3: PROPOSED STUDY MODEL INSIDE THE GWE WIND TUNNEL LOOKING DOWNWIND**

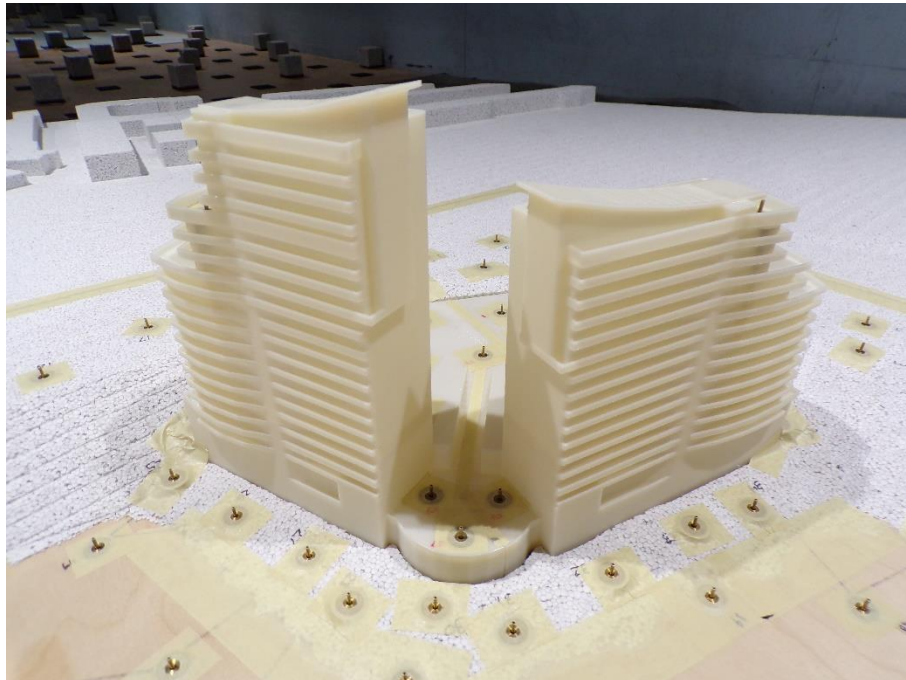


**PHOTOGRAPH 4: PROPOSED STUDY MODEL INSIDE THE GWE WIND TUNNEL LOOKING UPWIND**



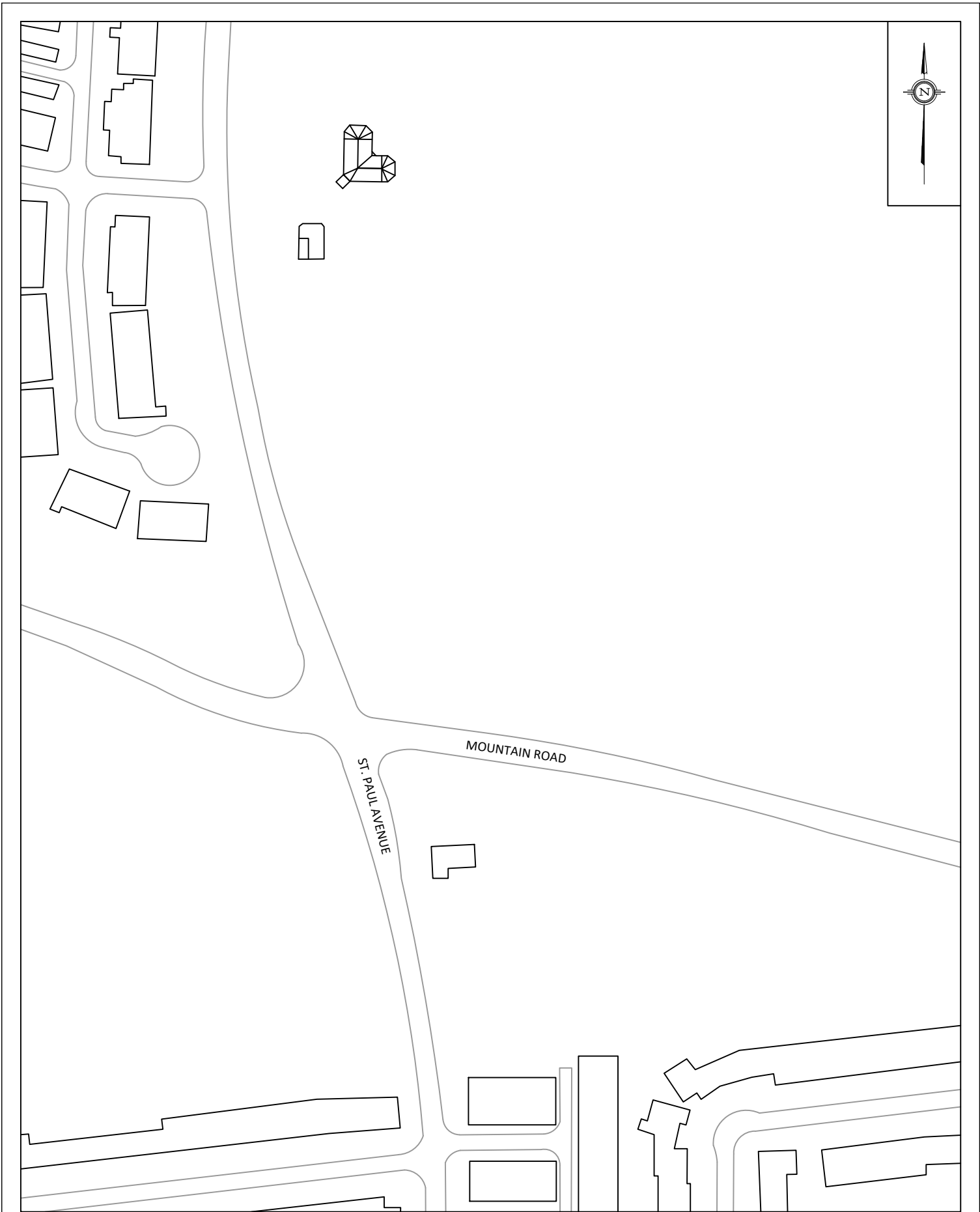


**PHOTOGRAPH 5: CLOSE-UP VIEW OF PROPOSED STUDY MODEL LOOKING NORTHEAST**

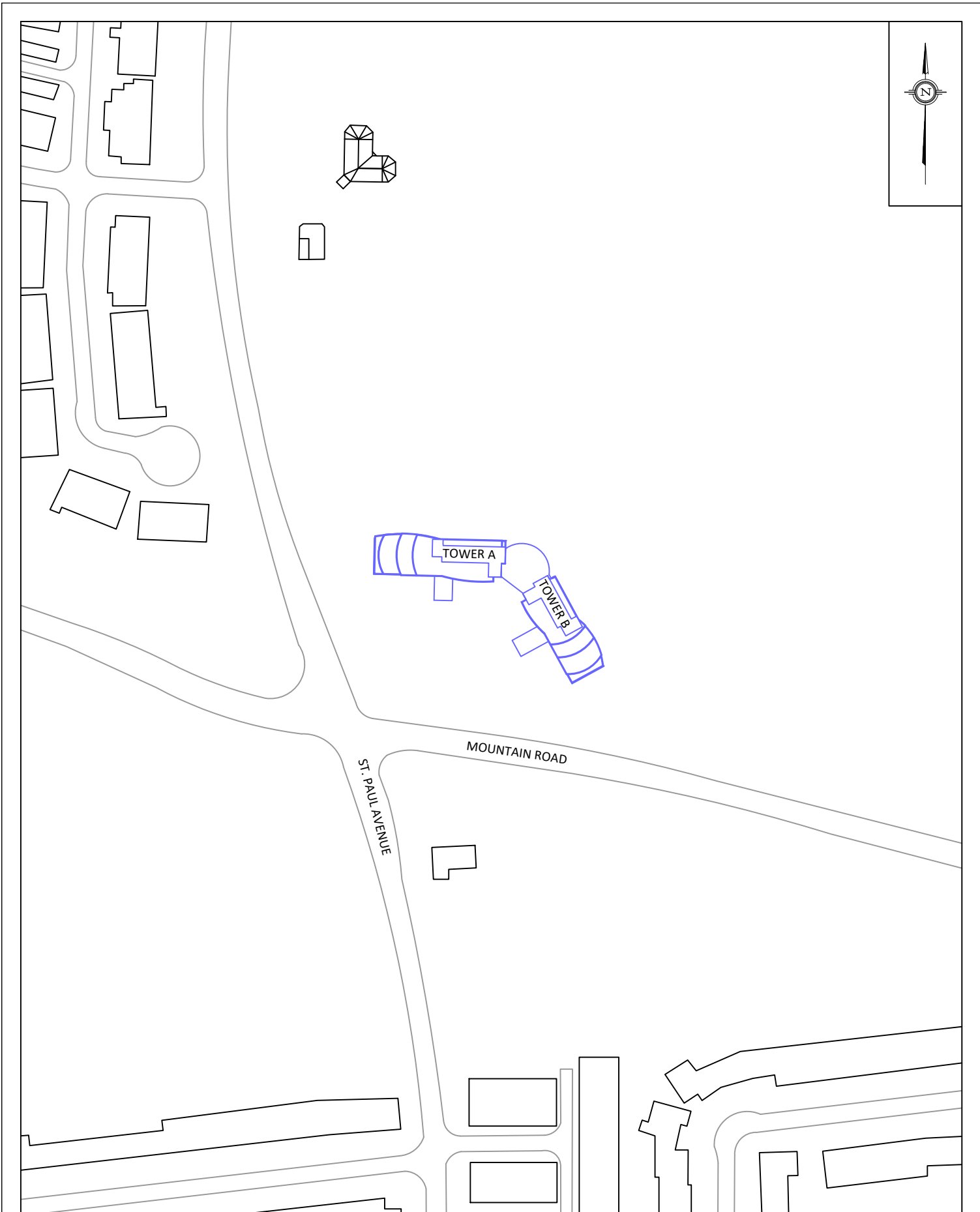


**PHOTOGRAPH 6: CLOSE-UP VIEW OF PROPOSED STUDY MODEL LOOKING SOUTHWEST**

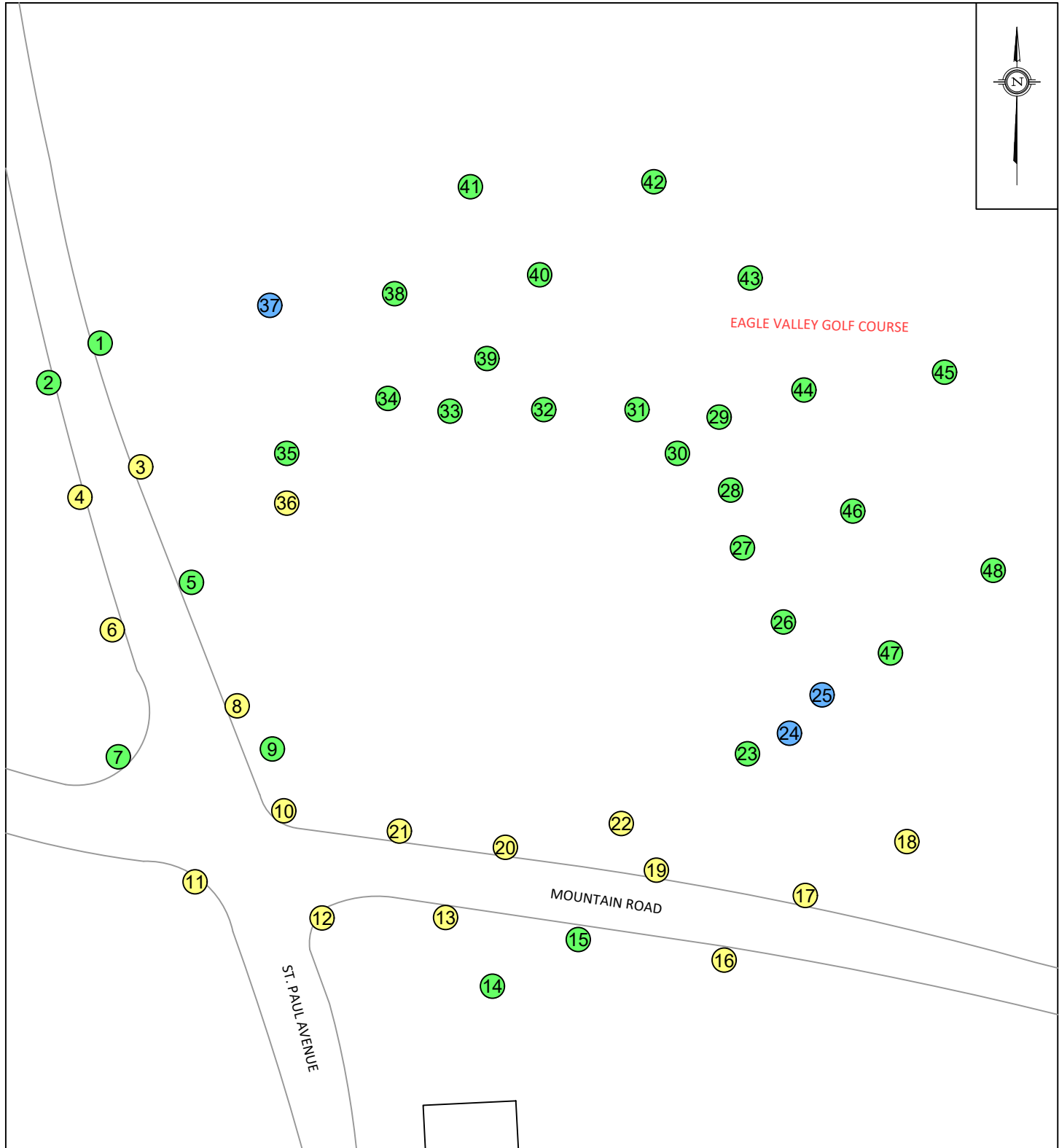




<b>GRADIENTWIND</b> ENGINEERS & SCIENTISTS 127 WALGREEN ROAD, OTTAWA, ON 613 836 0934 • GRADIENTWIND.COM	PROJECT 2430 ST. PAUL AVENUE, NIAGARA FALLS PEDESTRIAN LEVEL WIND STUDY		DESCRIPTION FIGURE 1A: EXISTING SCENARIO AND SURROUNDING CONTEXT
	SCALE 1:2500 (APPROX.)	DRAWING NO. GW23-238-PLW-1A	
	DATE JANUARY 10, 2024	DRAWN BY K.A.	



PROJECT	2430 ST. PAUL AVENUE, NIAGARA FALLS PEDESTRIAN LEVEL WIND STUDY	
SCALE	1:2500 (APPRX.)	DRAWING NO. GW23-238-PLW-1B
DATE	JANUARY 10, 2024	DRAWN BY K.A.

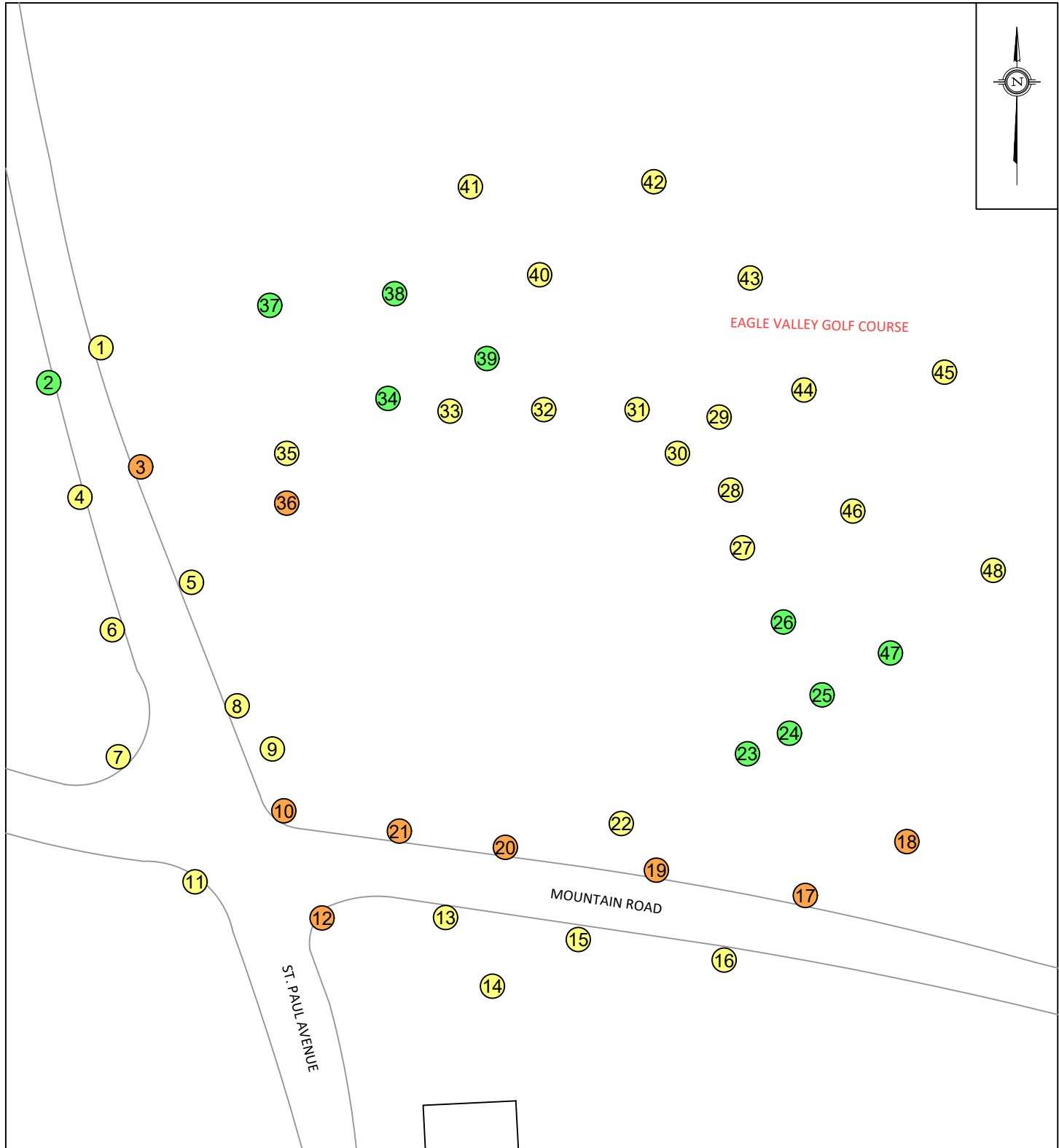


PREDICTED COMFORT CLASSES	# SITTING
	# STANDING
	# WALKING
	# UNCOMFORTABLE

WIND SAFETY CRITERION	# ACCEPTABLE
	# EXCEEDED

**NOTES:**

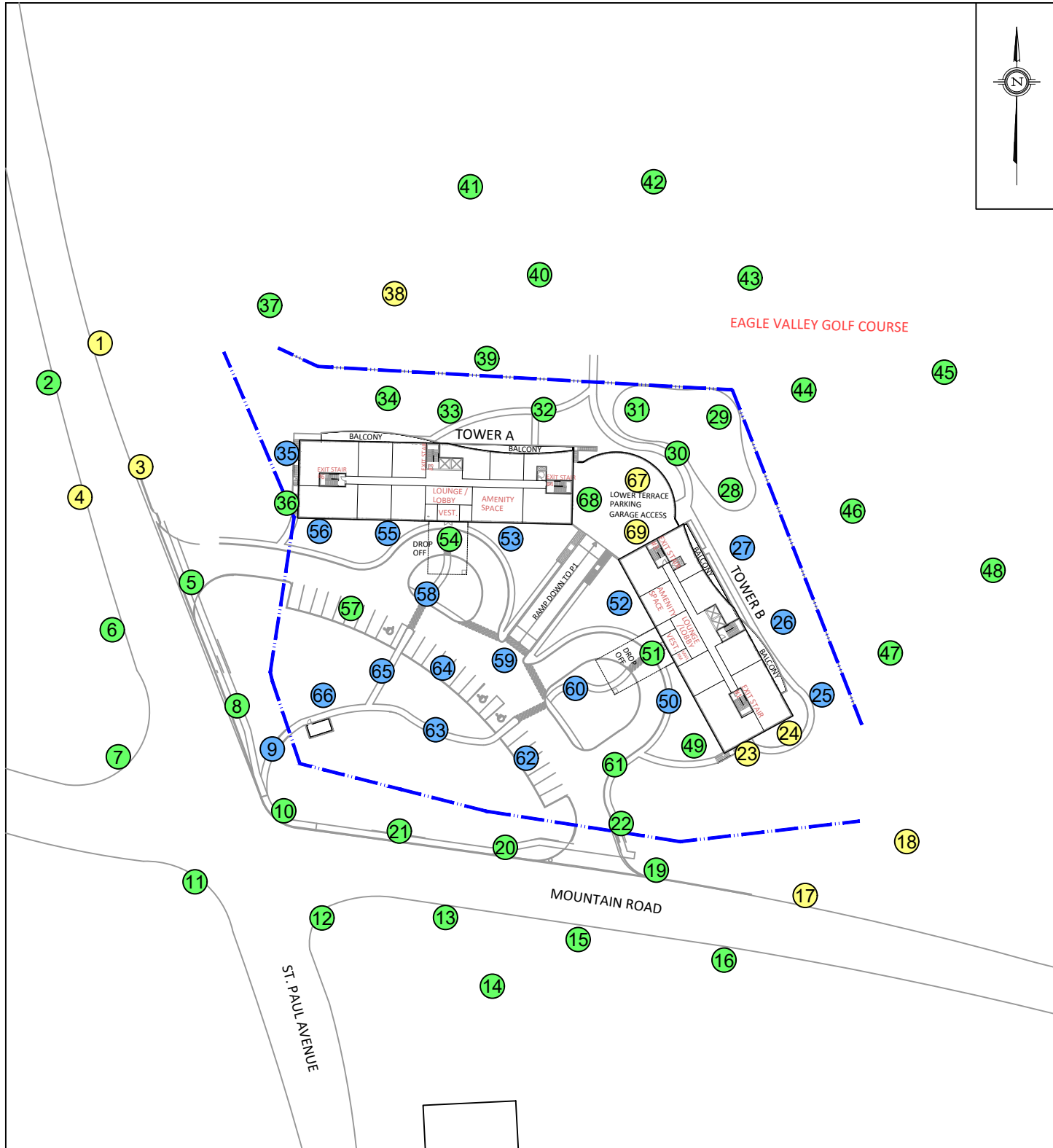
- SCALE IS APPROXIMATE.
- # PEDESTRIAN LEVEL WIND SENSOR LOCATION.



PREDICTED COMFORT CLASSES	# SITTING
	# STANDING
	# WALKING
	# UNCOMFORTABLE
WIND SAFETY CRITERION	# ACCEPTABLE
	# EXCEEDED

**NOTES:**

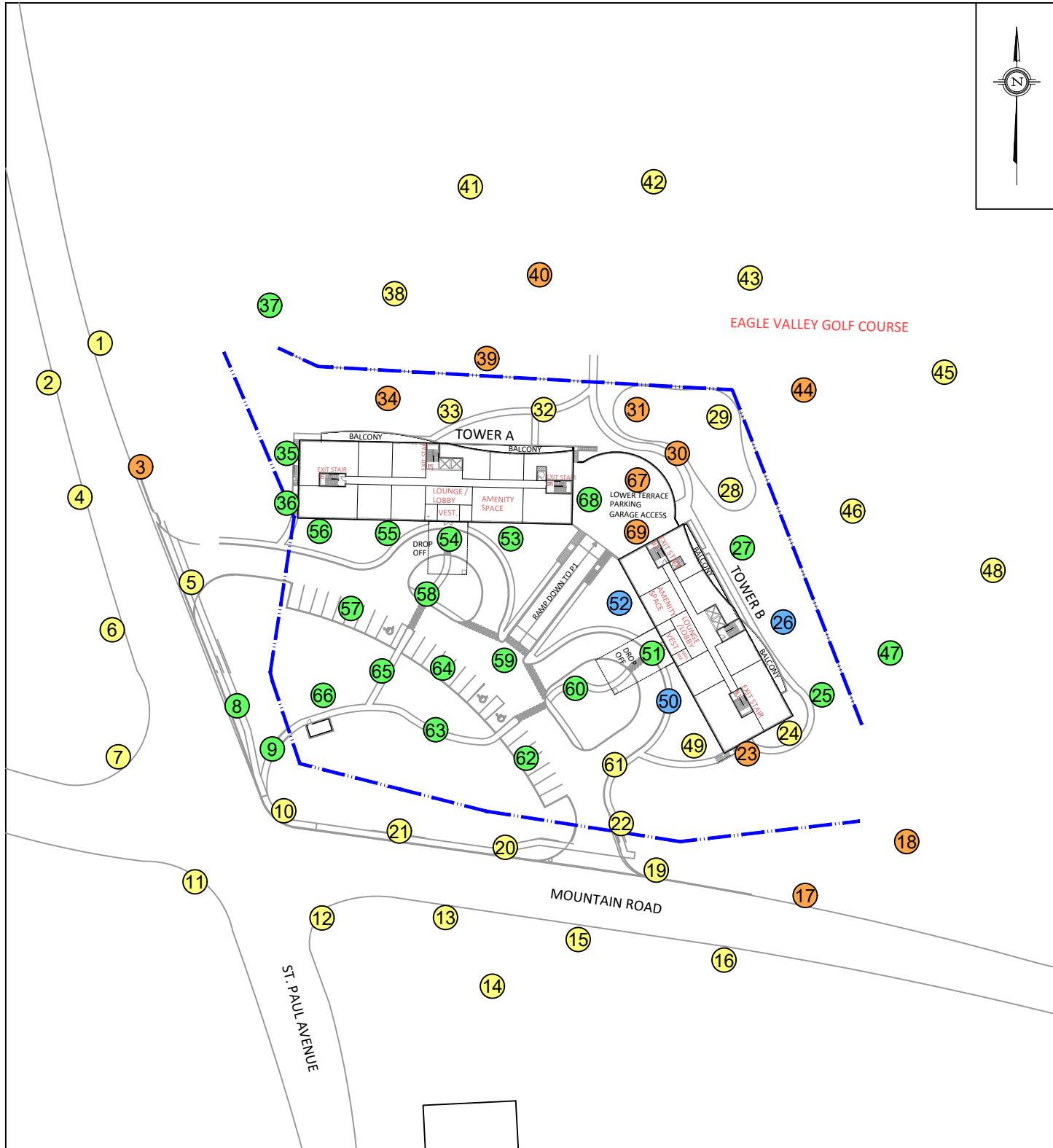
- SCALE IS APPROXIMATE.
- # PEDESTRIAN LEVEL WIND SENSOR LOCATION.



PREDICTED COMFORT CLASSES	<span style="color: blue;">#</span>	SITTING
	<span style="color: green;">#</span>	STANDING
	<span style="color: yellow;">#</span>	WALKING
	<span style="color: orange;">#</span>	UNCOMFORTABLE
WIND SAFETY CRITERION	<span style="border: 1px solid black; border-radius: 50%; padding: 2px;">#</span>	ACCEPTABLE
	<span style="border: 1px solid red; border-radius: 50%; padding: 2px;">#</span>	EXCEEDED

**NOTES:**

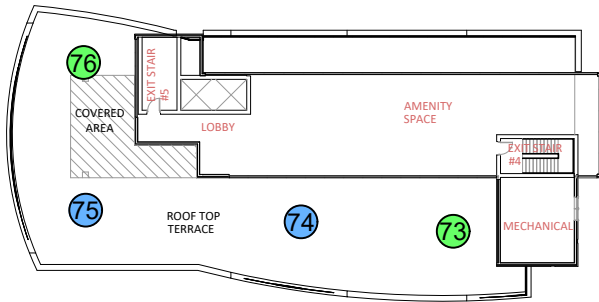
- SCALE IS APPROXIMATE.
- # PEDESTRIAN LEVEL WIND SENSOR LOCATION.



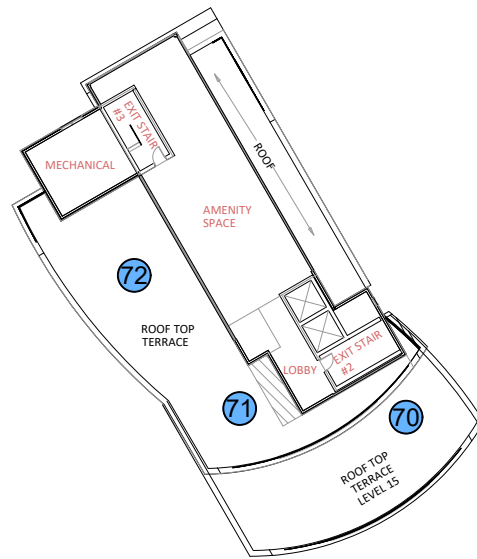
PREDICTED COMFORT CLASSES	<span style="color: blue;">#</span>	SITTING
	<span style="color: green;">#</span>	STANDING
	<span style="color: yellow;">#</span>	WALKING
	<span style="color: orange;">#</span>	UNCOMFORTABLE
WIND SAFETY CRITERION	<span style="border: 1px solid black; border-radius: 50%; padding: 2px;">#</span>	ACCEPTABLE
	<span style="border: 1px solid red; border-radius: 50%; padding: 2px;">#</span>	EXCEEDED

**NOTES:**

- SCALE IS APPROXIMATE.
- # PEDESTRIAN LEVEL WIND SENSOR LOCATION.



TOWER A

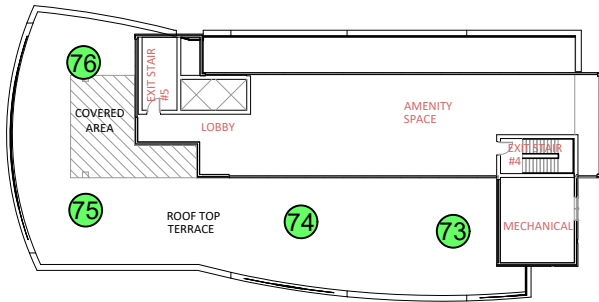


TOWER B

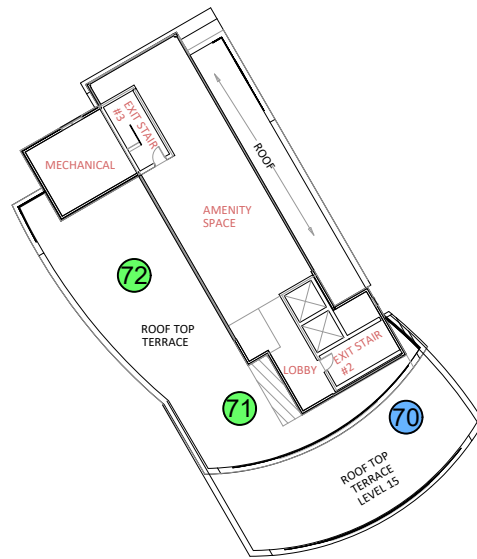
PREDICTED COMFORT CLASSES		SITTING
		STANDING
		WALKING
		UNCOMFORTABLE
WIND SAFETY CRITERION		ACCEPTABLE
		EXCEEDED

**NOTES:**  
 1. SCALE IS APPROXIMATE.  
 2. PEDESTRIAN LEVEL WIND SENSOR LOCATION.





TOWER A



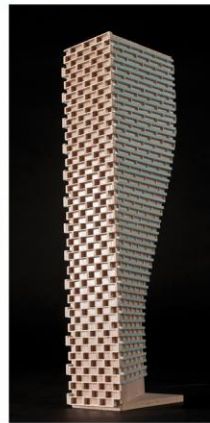
TOWER B

PREDICTED COMFORT CLASSES		SITTING
		STANDING
		WALKING
		UNCOMFORTABLE
WIND SAFETY CRITERION		ACCEPTABLE
		EXCEEDED

**NOTES:**  
 1. SCALE IS APPROXIMATE.  
 2. PEDESTRIAN LEVEL WIND SENSOR LOCATION.

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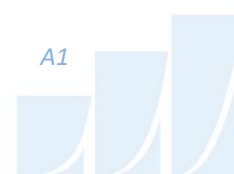
## APPENDIX A

### PEDESTRIAN COMFORT SUITABILITY, TABLES A1-A2 (EXISTING SCENARIO)

Guidelines	
Pedestrian Comfort	<b>20% exceedance wind speed</b> 0-10 km/h = Sitting, 10-15 km/h = Standing, 15-20 km/h = Walking, >20 km/h = Uncomfortable
Pedestrian Safety	<b>0.1% exceedance wind speed</b> 0-90 km/h = Safe

**TABLE A1: SUMMARY OF PEDESTRIAN COMFORT (EXISTING SCENARIO)**

Sensor	Pedestrian Comfort				Pedestrian Safety	
	Summer		Winter		Annual	
	Wind Speed	Comfort Class	Wind Speed	Comfort Class	Wind Speed	Safety Class
1	13.9	Standing	17.1	Walking	53.0	Safe
2	12.1	Standing	14.8	Standing	45.2	Safe
3	17.7	Walking	21.7	Uncomfortable	66.1	Safe
4	15.6	Walking	19.5	Walking	59.7	Safe
5	15.0	Standing	18.6	Walking	56.6	Safe
6	15.3	Walking	19.1	Walking	57.5	Safe
7	14.9	Standing	18.3	Walking	55.7	Safe
8	15.7	Walking	19.7	Walking	58.9	Safe
9	15.0	Standing	18.9	Walking	57.1	Safe
10	16.3	Walking	20.5	Uncomfortable	60.0	Safe
11	15.8	Walking	19.7	Walking	57.9	Safe
12	15.8	Walking	20.4	Uncomfortable	59.2	Safe
13	15.3	Walking	20.0	Walking	59.8	Safe
14	15.0	Standing	19.9	Walking	60.4	Safe
15	14.4	Standing	19.0	Walking	58.7	Safe
16	15.6	Walking	20.0	Walking	57.0	Safe
17	16.0	Walking	20.4	Uncomfortable	59.5	Safe
18	16.9	Walking	20.9	Uncomfortable	59.8	Safe
19	16.0	Walking	20.1	Uncomfortable	58.5	Safe
20	18.0	Walking	22.1	Uncomfortable	63.6	Safe
21	19.7	Walking	24.1	Uncomfortable	70.4	Safe
22	15.4	Walking	18.8	Walking	57.9	Safe
23	10.2	Standing	14.0	Standing	45.0	Safe
24	9.1	Sitting	12.7	Standing	39.6	Safe
25	9.7	Sitting	13.2	Standing	41.2	Safe
26	11.2	Standing	14.8	Standing	47.6	Safe
27	12.2	Standing	15.7	Walking	47.0	Safe
28	13.4	Standing	17.1	Walking	49.9	Safe
29	12.2	Standing	15.8	Walking	47.4	Safe
30	12.9	Standing	16.8	Walking	48.9	Safe
31	13.3	Standing	17.1	Walking	50.0	Safe
32	13.4	Standing	17.1	Walking	51.4	Safe
33	12.8	Standing	15.9	Walking	47.6	Safe
34	11.1	Standing	13.7	Standing	42.8	Safe
35	12.2	Standing	16.0	Walking	51.5	Safe



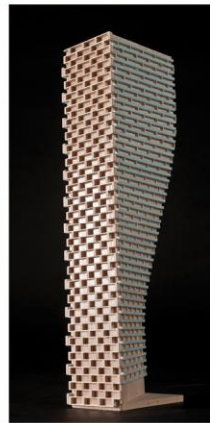
Guidelines	
Pedestrian Comfort	<b>20% exceedance wind speed</b> 0-10 km/h = Sitting, 10-15 km/h = Standing, 15-20 km/h = Walking, >20 km/h = Uncomfortable
Pedestrian Safety	<b>0.1% exceedance wind speed</b> 0-90 km/h = Safe

**TABLE A2: SUMMARY OF PEDESTRIAN COMFORT (EXISTING SCENARIO)**

Sensor	Pedestrian Comfort				Pedestrian Safety	
	Summer		Winter		Annual	
	Wind Speed	Comfort Class	Wind Speed	Comfort Class	Wind Speed	Safety Class
<b>36</b>	18.4	Walking	22.9	Uncomfortable	67.1	Safe
<b>37</b>	8.5	Sitting	10.7	Standing	35.2	Safe
<b>38</b>	11.5	Standing	14.4	Standing	45.0	Safe
<b>39</b>	12.0	Standing	15.0	Standing	46.6	Safe
<b>40</b>	13.7	Standing	17.1	Walking	50.4	Safe
<b>41</b>	13.5	Standing	17.0	Walking	50.8	Safe
<b>42</b>	14.4	Standing	18.0	Walking	52.9	Safe
<b>43</b>	14.3	Standing	18.2	Walking	52.8	Safe
<b>44</b>	13.6	Standing	17.4	Walking	50.0	Safe
<b>45</b>	14.4	Standing	18.2	Walking	53.8	Safe
<b>46</b>	13.0	Standing	16.9	Walking	50.1	Safe
<b>47</b>	10.3	Standing	14.0	Standing	45.1	Safe
<b>48</b>	12.4	Standing	16.7	Walking	51.3	Safe

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## APPENDIX B

### PEDESTRIAN COMFORT SUITABILITY, TABLES B1-B3 (PROPOSED SCENARIO)

Guidelines	
Pedestrian Comfort	<b>20% exceedance wind speed</b> 0-10 km/h = Sitting, 10-15 km/h = Standing, 15-20 km/h = Walking, >20 km/h = Uncomfortable
Pedestrian Safety	<b>0.1% exceedance wind speed</b> 0-90 km/h = Safe

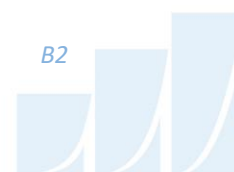
**TABLE B1: SUMMARY OF PEDESTRIAN COMFORT (PROPOSED SCENARIO)**

Sensor	Pedestrian Comfort				Pedestrian Safety	
	Summer		Winter		Annual	
	Wind Speed	Comfort Class	Wind Speed	Comfort Class	Wind Speed	Safety Class
<b>1</b>	15.2	Walking	18.1	Walking	56.7	Safe
<b>2</b>	13.6	Standing	15.6	Walking	48.7	Safe
<b>3</b>	18.5	Walking	22.1	Uncomfortable	68.3	Safe
<b>4</b>	15.9	Walking	19.1	Walking	59.1	Safe
<b>5</b>	12.7	Standing	15.3	Walking	48.6	Safe
<b>6</b>	13.2	Standing	16.3	Walking	51.0	Safe
<b>7</b>	11.8	Standing	15.2	Walking	46.3	Safe
<b>8</b>	10.1	Standing	13.5	Standing	45.6	Safe
<b>9</b>	9.5	Sitting	12.8	Standing	45.1	Safe
<b>10</b>	12.0	Standing	16.0	Walking	48.4	Safe
<b>11</b>	13.1	Standing	17.2	Walking	50.8	Safe
<b>12</b>	12.9	Standing	17.5	Walking	51.6	Safe
<b>13</b>	12.5	Standing	17.0	Walking	51.6	Safe
<b>14</b>	13.5	Standing	19.0	Walking	55.4	Safe
<b>15</b>	12.5	Standing	17.7	Walking	53.8	Safe
<b>16</b>	14.8	Standing	20.0	Walking	58.8	Safe
<b>17</b>	17.6	Walking	23.0	Uncomfortable	67.7	Safe
<b>18</b>	19.5	Walking	25.4	Uncomfortable	79.3	Safe
<b>19</b>	12.8	Standing	17.5	Walking	54.5	Safe
<b>20</b>	11.0	Standing	15.2	Walking	49.9	Safe
<b>21</b>	12.3	Standing	17.0	Walking	52.3	Safe
<b>22</b>	10.8	Standing	15.0	Walking	49.1	Safe
<b>23</b>	17.4	Walking	23.1	Uncomfortable	78.4	Safe
<b>24</b>	15.6	Walking	19.7	Walking	71.2	Safe
<b>25</b>	9.8	Sitting	12.2	Standing	43.3	Safe
<b>26</b>	8.1	Sitting	10.0	Sitting	41.4	Safe
<b>27</b>	9.6	Sitting	14.1	Standing	53.0	Safe
<b>28</b>	13.0	Standing	18.7	Walking	68.1	Safe
<b>29</b>	13.9	Standing	19.9	Walking	60.6	Safe
<b>30</b>	14.4	Standing	20.2	Uncomfortable	63.0	Safe
<b>31</b>	14.3	Standing	20.4	Uncomfortable	61.0	Safe
<b>32</b>	12.1	Standing	18.9	Walking	61.7	Safe
<b>33</b>	10.7	Standing	16.7	Walking	67.3	Safe
<b>34</b>	13.5	Standing	20.1	Uncomfortable	84.3	Safe
<b>35</b>	9.5	Sitting	12.2	Standing	50.1	Safe

Guidelines	
Pedestrian Comfort	<b>20% exceedance wind speed</b> 0-10 km/h = Sitting, 10-15 km/h = Standing, 15-20 km/h = Walking, >20 km/h = Uncomfortable
Pedestrian Safety	<b>0.1% exceedance wind speed</b> 0-90 km/h = Safe

**TABLE B2: SUMMARY OF PEDESTRIAN COMFORT (PROPOSED SCENARIO)**

Sensor	Pedestrian Comfort				Pedestrian Safety	
	Summer		Winter		Annual	
	Wind Speed	Comfort Class	Wind Speed	Comfort Class	Wind Speed	Safety Class
36	10.8	Standing	13.8	Standing	51.7	Safe
37	10.5	Standing	12.6	Standing	45.9	Safe
38	15.3	Walking	19.4	Walking	72.1	Safe
39	14.7	Standing	20.9	Uncomfortable	79.0	Safe
40	14.7	Standing	20.3	Uncomfortable	72.4	Safe
41	14.8	Standing	19.5	Walking	65.1	Safe
42	13.9	Standing	19.1	Walking	62.5	Safe
43	13.8	Standing	19.4	Walking	62.9	Safe
44	14.0	Standing	20.2	Uncomfortable	65.1	Safe
45	13.7	Standing	19.4	Walking	63.2	Safe
46	13.4	Standing	19.8	Walking	65.2	Safe
47	10.3	Standing	12.6	Standing	46.2	Safe
48	12.3	Standing	16.5	Walking	53.1	Safe
49	13.5	Standing	19.1	Walking	67.1	Safe
50	7.4	Sitting	9.9	Sitting	37.5	Safe
51	10.1	Standing	13.8	Standing	49.3	Safe
52	7.5	Sitting	9.7	Sitting	36.3	Safe
53	8.8	Sitting	12.2	Standing	50.7	Safe
54	10.3	Standing	13.7	Standing	55.5	Safe
55	7.2	Sitting	10.8	Standing	44.3	Safe
56	9.6	Sitting	11.7	Standing	47.0	Safe
57	11.1	Standing	14.7	Standing	53.8	Safe
58	9.7	Sitting	13.1	Standing	48.6	Safe
59	9.9	Sitting	12.2	Standing	54.0	Safe
60	7.9	Sitting	10.4	Standing	39.3	Safe
61	12.5	Standing	17.3	Walking	56.4	Safe
62	9.4	Sitting	12.8	Standing	46.4	Safe
63	9.8	Sitting	13.1	Standing	54.0	Safe
64	8.6	Sitting	11.6	Standing	49.8	Safe
65	9.9	Sitting	13.7	Standing	55.7	Safe
66	9.7	Sitting	14.1	Standing	47.1	Safe
67	16.3	Walking	21.1	Uncomfortable	71.8	Safe
68	12.9	Standing	14.4	Standing	76.4	Safe
69	18.0	Walking	22.6	Uncomfortable	79.0	Safe
70	8.4	Sitting	10.0	Sitting	44.1	Safe



Guidelines	
Pedestrian Comfort	<b>20% exceedance wind speed</b> 0-10 km/h = Sitting, 10-15 km/h = Standing, 15-20 km/h = Walking, >20 km/h = Uncomfortable
Pedestrian Safety	<b>0.1% exceedance wind speed</b> 0-90 km/h = Safe

**TABLE B3: SUMMARY OF PEDESTRIAN COMFORT (PROPOSED SCENARIO)**

Sensor	Pedestrian Comfort				Pedestrian Safety	
	Summer		Winter		Annual	
	Wind Speed	Comfort Class	Wind Speed	Comfort Class	Wind Speed	Safety Class
<b>71</b>	8.4	Sitting	12.2	Standing	52.5	Safe
<b>72</b>	8.8	Sitting	13.1	Standing	61.1	Safe
<b>73</b>	11.1	Standing	15.0	Standing	60.0	Safe
<b>74</b>	9.6	Sitting	14.1	Standing	63.3	Safe
<b>75</b>	8.8	Sitting	11.1	Standing	45.9	Safe
<b>76</b>	10.4	Standing	12.4	Standing	62.4	Safe



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## APPENDIX C

### WIND TUNNEL SIMULATION OF THE NATURAL WIND

## 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 metres (m) to 600 m.

Simulating real wind behaviour in a wind tunnel 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  $\alpha$  is the power law exponent.

Figure B1 on the following page plots three velocity profiles for open country, and suburban and urban exposures.

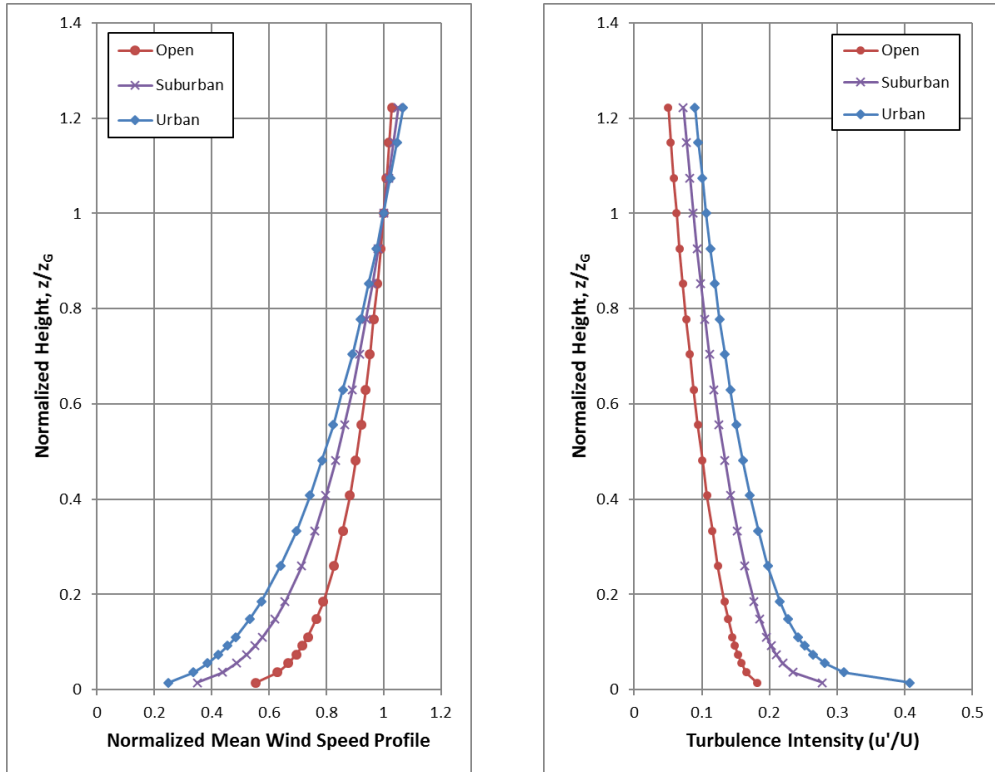
The exponent  $\alpha$  varies according to the type of upwind terrain;  $\alpha$  ranges from 0.14 for open country to 0.33 for an urban exposure. Figure C2 illustrates the theoretical variation of turbulence for open country, suburban and urban exposures.

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

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

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

Once the wind simulation is correct, the model, constructed to a suitable scale, is installed at the 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.



**FIGURE C1 (LEFT): MEAN WIND SPEED PROFILES;  
FIGURE C2 (RIGHT): TURBULENCE INTENSITY PROFILES**

## 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*', 9<sup>th</sup> Australian Fluid Mechanics Conference, Auckland, Dec. 1966



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## APPENDIX D

### PEDESTRIAN LEVEL WIND MEASUREMENT METHODOLOGY

## **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 D1. 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:

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

Where,

$P(> U_g)$  is the probability, fraction of time, that the gradient wind speed  $U_g$  is exceeded;  $\theta$  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  $10^\circ$  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:

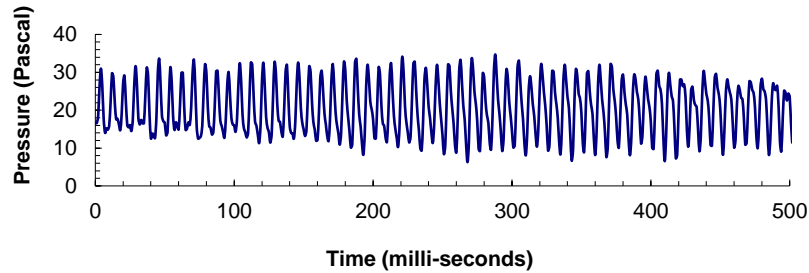
$$P_N(> 20) = \sum_\theta P \left[ \frac{(> 20)}{\left( \frac{U_N}{U_g} \right)} \right]$$

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

Where,  $U_N / U_g$  is the gust velocity ratios, where the summation is taken over all 36 wind directions at  $10^\circ$  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 D1: 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.