2.1 Spectator Player Wind Comfort Study, BMT FLUID MECHANICS

BMT Fluid Mechanics

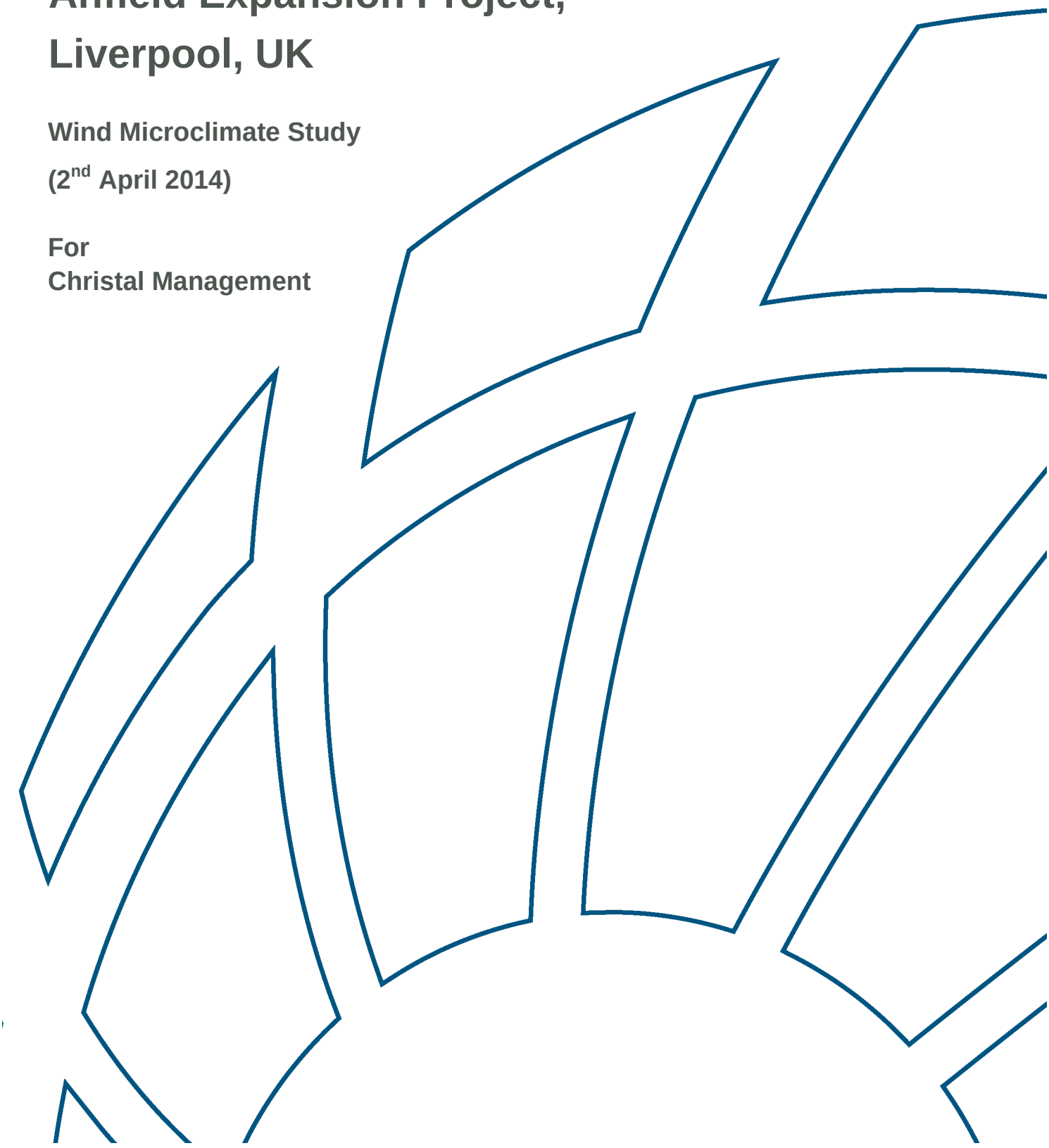
Project No. 431590

Anfield Expansion Project, Liverpool, UK

Wind Microclimate Study

(2nd April 2014)

For
Christal Management



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Anfield Expansion Project
Wind Microclimate Study

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EXECUTIVE SUMMARY

Background

A boundary layer wind tunnel study has been carried out by BMT Fluid Mechanics Ltd. (BMT) to assess the pedestrian level wind environment for the proposed Anfield Stadium Expansion in Liverpool, UK.

The study has provided a detailed quantitative assessment of the wind environment at key locations around the proposed development in terms of accepted, industry standard, pedestrian comfort and safety criteria. More specifically, the study assesses the impact of the addition of a revised Main stand and a revised Anfield Road stand on the pedestrian comfort within and around the site.

The report includes full details of the assessment methodology adopted in the study. The study combines measured pedestrian level wind speeds at key areas in and around the site (from model-scale boundary layer wind tunnel testing) with long-term wind frequency statistics (transposed from the nearest suitable weather centre to apply directly at the site), to determine the probability of local wind speeds exceeding comfort and safety thresholds for a range of common pedestrian activities based on the Lawson criteria (see Appendix C). This defines the type of activities for which the wind conditions would be safe and comfortable. An area that has relatively low wind speeds and would be comfortable for recreational use (involving standing or sitting) would also be suitable for uses that tolerate higher wind speeds such as walking.

Conclusions

Existing Configuration

With regards to pedestrian safety, wind conditions within and around the site with are deemed suitable.

With regards to pedestrian comfort wind conditions within and around the site with are deemed suitable for the intended uses, including all entrances and thoroughfares.

Phase 1 and 2

With regards to pedestrian safety, wind conditions within and around the site with are deemed suitable for both the Phase 1 and Phase 2 configurations.

With regards to pedestrian comfort wind conditions within and around the site with are generally deemed suitable for the intended uses, including all

entrances and thoroughfares. An exception occurs at the proposed recreational space at the north-west corner of the new Main stand where wind conditions are considered too windy for outdoor recreational activities that would involve short duration stationary activities on a frequent basis. However, should this area be primarily used for thoroughfare purposes wind conditions would be considered acceptable.

Anfield Expansion Project, Wind Microclimate Study

1. Introduction

A boundary layer wind tunnel study has been carried out by BMT Fluid Mechanics Ltd. (BMT) to assess the pedestrian level wind environment for the proposed Anfield Stadium Expansion in Liverpool, UK.

The study has provided a detailed quantitative assessment of the wind environment at key locations around the proposed development in terms of accepted, industry standard, pedestrian comfort and safety criteria. More specifically, the study assesses the impact of the addition of a revised Main stand and a revised Anfield Road stand on the pedestrian comfort within and around the site.

2. Assessment Methodology

2.1. Boundary Layer Wind Tunnel Studies

The assessment of environmental wind flows in the built environment lies outside the scope of BS EN 1991-1-4:2005, the current European Standard for wind actions on structures, which focuses on wind loading issues. In addition, there are no handbooks or engineering methods from which reliable assessments of the complex environmental wind flows that shape the pedestrian level wind conditions can be derived and numerical / computational methods such as computational fluid dynamics do not apply to turbulent wind flows in the built environment.

As a result, a purposely-designed boundary layer wind tunnel study was used to provide a reliable quantification of the pedestrian level wind environment at the following key locations:

- Pedestrian access routes
- Entrances
- Outdoor Seating Areas

The study combines pedestrian level wind speed-up at key areas in and around the site with long-term wind frequency statistics for the site, to determine the probability of local wind speeds exceeding comfort and safety thresholds for a range of common pedestrian activities. The threshold wind speeds are based on the industry standard Lawson criteria. The wind speed-ups are measured in the model-scale boundary layer wind tunnel testing for a full range of wind directions. The wind statistics are transposed from the nearest suitable weather centre to apply directly at the site.

2.2. Wind Analysis

Details of the annual and seasonal climate wind analysis relevant to the site are presented in Appendix A.

2.3. Wind Tunnel and Model Details

Details of the model scale and construction, along with photos of the model and wind tunnel setup are presented in Appendix B.

The model scale of 1:250 is large enough to allow a good representation of the details that are likely to affect the local and overall wind flows at full scale. In addition, this scale enables a good simulation of the turbulence properties of the wind to be achieved.

2.4. Measurement and Analysis

The technical details relating to the instrumentation, measurements and analysis for the wind environment study along with the assessment criteria to which they are compared (Lawson criteria) are described in Appendix C.

The Lawson criterion defines the type of activities for which the wind conditions would be safe and comfortable. An area that has relatively low wind speeds and would be comfortable for recreational use (involving standing or sitting) would also be suitable for uses that tolerate higher wind speeds such as walking.

The wind environment was assessed at a total of 50 pedestrian locations for each configuration. Details of the measurement location schemes are shown in Figures 5.1 to 5.3. Details of proposed pedestrian activities, assumed in the assessment, are also provided in Appendix C.

Measurements were taken for a full range of wind directions in increments of 22.5°.

2.5. Wind Direction

The 0° wind direction has been chosen to coincide with the OS Grid north (90° east, 180° south, 270° west). The wind direction denotes the direction, which the wind is blowing *from*, as shown in Figure 2.1.

3. Site / Proposed Development

3.1. Location / Surrounding Area

The Anfield Stadium is located in Liverpool, UK. The immediate existing surrounding area generally consists of low-rise residential housing to the south, east and west, and open parkland in the north.

3.2. Existing Stadium

The existing stadium consists of four stands, namely the Kop (at the southern aspect), the present Main stand (eastern aspect), the Anfield Road stand (northern aspect) and the Centenary Stand (western aspect).

3.3. Proposed Stadium Expansion

It is proposed that the stadium will expand over two phases, namely Phase 1, in which the present Main stand will be demolished and replaced with a larger Main stand; and Phase 2, where the present Anfield Road stand will then be demolished and replaced with a larger stand.

4. Results

4.1. General

Results are provided for the following three configurations:

- Existing configuration
- Phase 1, with the new Main Stand
- Phase 2, with both the new Anfield Road stand and new Main Stand

4.2. Annual and Seasonal Assessments (Appendix D)

The results of the wind speed measurements are summarised in graphical format in Appendix D, on CD, in terms of comfort and safety criteria derived for each pedestrian level measurement location.

5. Assessment

5.1. Approach to Assessment

5.1.1. Pedestrian Safety

At each area investigated, the suitability of the pedestrian level wind environment in terms of safety is assessed based on the Lawson criteria for pedestrian safety (see Appendix C). Safety is determined for the 'able-bodied' and for the 'general public'. For the general public a wind speed of 15m/s occurring once per year is rated as unsafe, with the potential to de-stabilise the less able members of the public including the elderly, cyclists and children. Able-bodied users are more likely to be capable of defending themselves against extreme pedestrian level winds and thus experience distress at a higher threshold wind speed of 20m/s, once per year.

5.1.2. Pedestrian Comfort

At each area investigated, the suitability of the pedestrian level wind environment in terms of comfort for various activities is assessed based on the Lawson criteria for pedestrian comfort (see Appendix C). The assessment takes full account of seasonal variations in wind conditions and pedestrian activities. For example, conditions for recreational activities focus on summer, but also consider spring and autumn, whilst conditions for pedestrian thoroughfare, access or waiting (example bus stops) consider all seasons,

with winter usually being the critical season. The activities considered, and their relation to the Lawson comfort criteria, are summarised as follows:

Suitability		Lawson Comfort Criteria
Outdoor Seating	For long periods of sitting such as for an outdoor café	'Long term sitting' in summer
Entrances, Waiting areas	For pedestrian ingress/egress at a building entrance, or short periods of sitting or standing such as at a bus stop, taxi rank, meeting point, etc.	'Standing or short term sitting' in all seasons
General Leisure (excluding seating areas)	For leisure uses excluding long periods of outdoor sitting such as a park, children's play area, etc.	'Standing or short term sitting' from spring to autumn
Thoroughfare	For access to and passage through the development and surrounding area	'Business walking' / 'Walking or strolling' in all seasons

5.2. Existing Conditions

The assessment of the wind environment for the Existing site conditions is shown in graphical format in Figure 5.1.

5.2.1. Pedestrian Safety

With regards to pedestrian safety, wind conditions within and around the site with are deemed suitable.

5.2.2. Pedestrian Comfort

With regards to pedestrian comfort wind conditions within and around the site with are deemed suitable for the intended uses, including all entrances and thoroughfares.

5.3. Phase 1 Conditions

The assessment of the wind environment for the Phase 1 site conditions is shown in graphical format in Figure 5.2.

5.3.1. Pedestrian Safety

With regards to pedestrian safety, wind conditions within and around the site with are deemed suitable.

5.3.2. Pedestrian Comfort

With regards to pedestrian comfort wind conditions within and around the site with are generally deemed suitable for the intended uses, including all entrances and thoroughfares. An exception occurs at the proposed recreational space at the north-west corner of the new Main stand (Location 116), where wind conditions are considered too windy for outdoor recreational activities that would involve short duration stationary activities on a frequent basis. However, should this area be primarily used for thoroughfare purposes wind conditions would be considered acceptable.

5.4. Phase 2 Conditions

The assessment of the wind environment for the Phase 2 site conditions is shown in graphical format in Figure 5.3.

5.4.1. Pedestrian Safety

With regards to pedestrian safety, wind conditions within and around the site with are deemed suitable.

5.4.2. Pedestrian Comfort

With regards to pedestrian comfort wind conditions within and around the site with are generally deemed suitable for the intended uses, including all entrances and thoroughfares. An exception occurs at the proposed recreational space at the north-west corner of the new Main stand (Location 116), where wind conditions are considered too windy for outdoor recreational activities that would involve short duration stationary activities on a frequent basis. However, should this area be primarily used for thoroughfare purposes wind conditions would be considered acceptable.

Figure 2.1: Site Plan and Wind Direction Definition

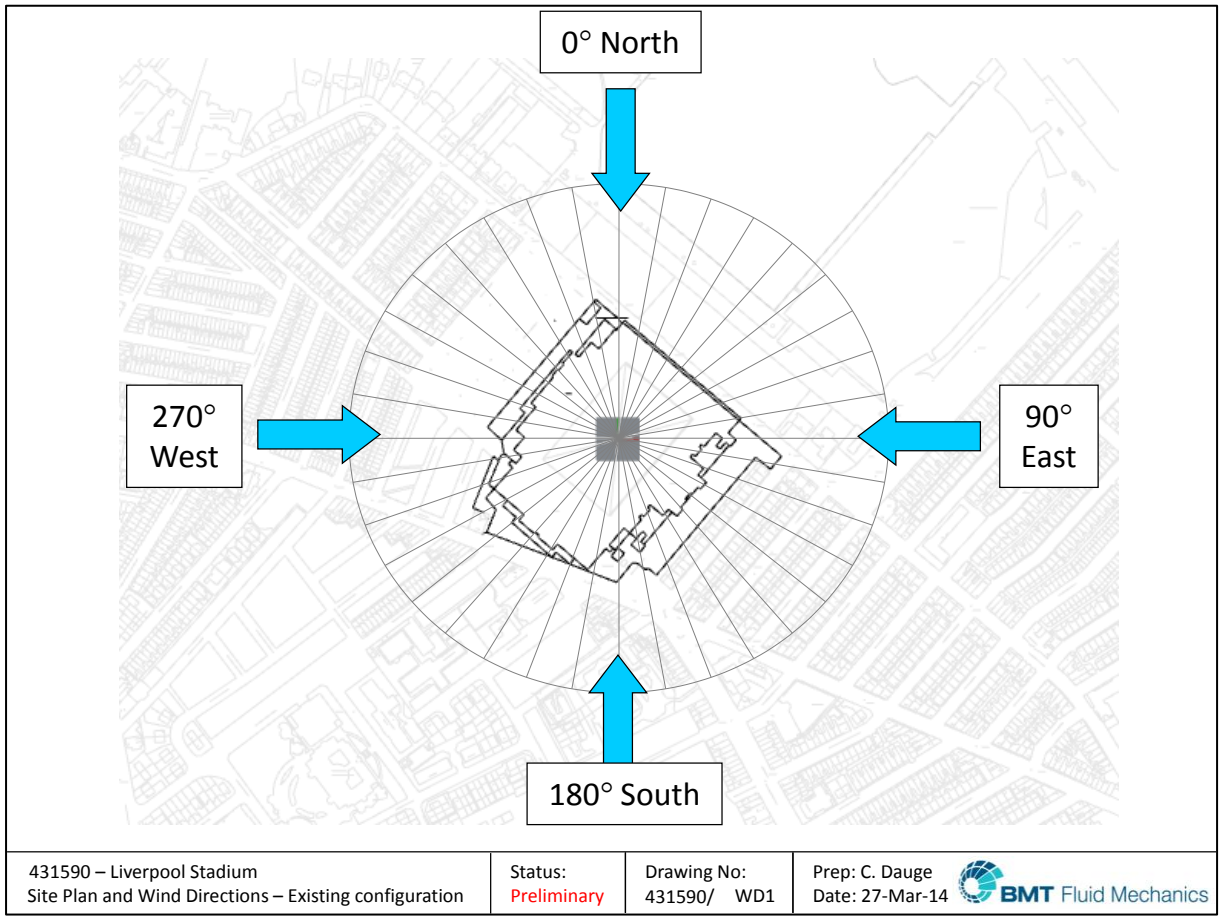


Figure 5.1: Pedestrian Level Wind Environment, Suitability Assessment: Existing configuration

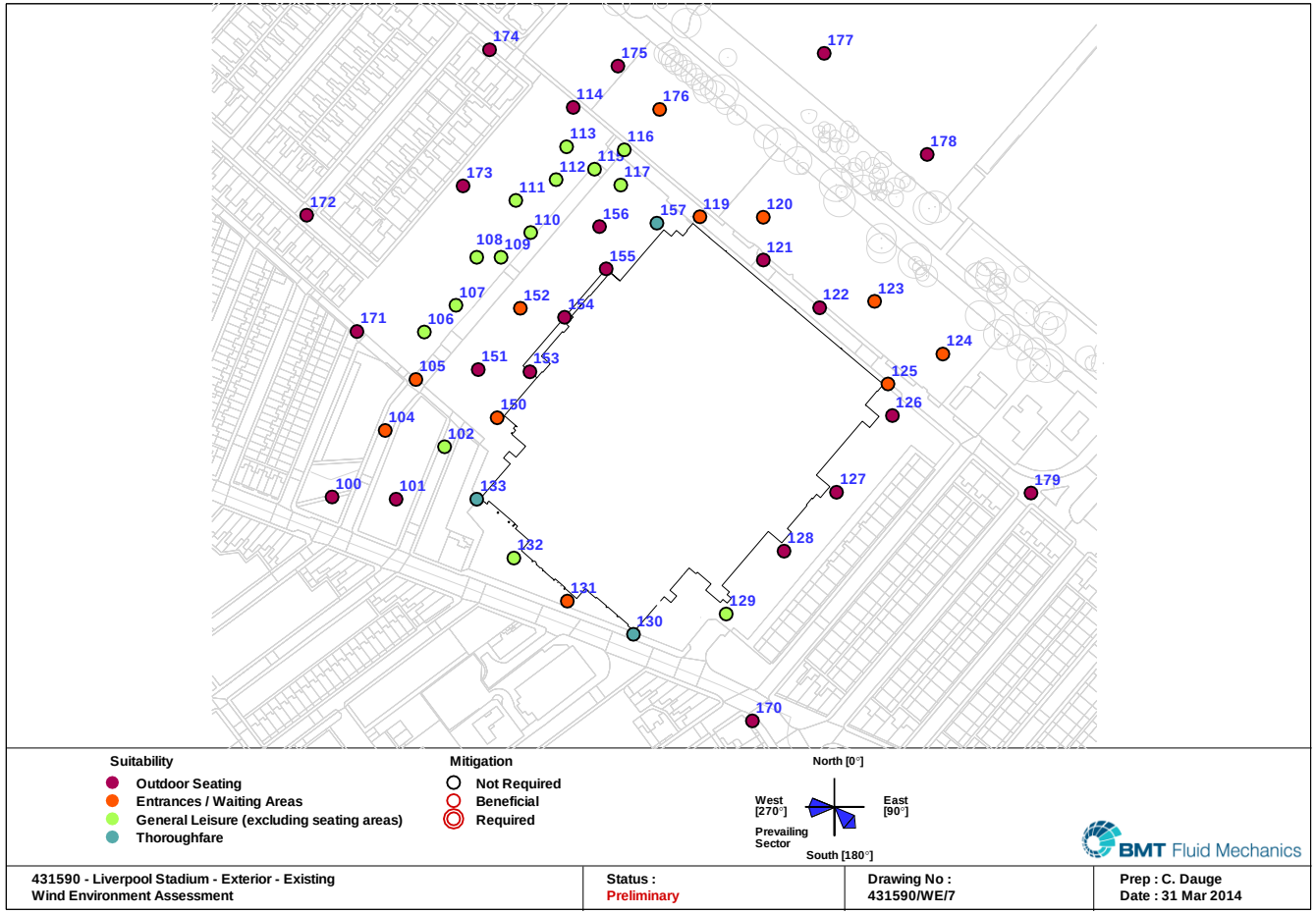


Figure 5.2: Pedestrian Level Wind Environment, Suitability Assessment: Phase 1 configuration

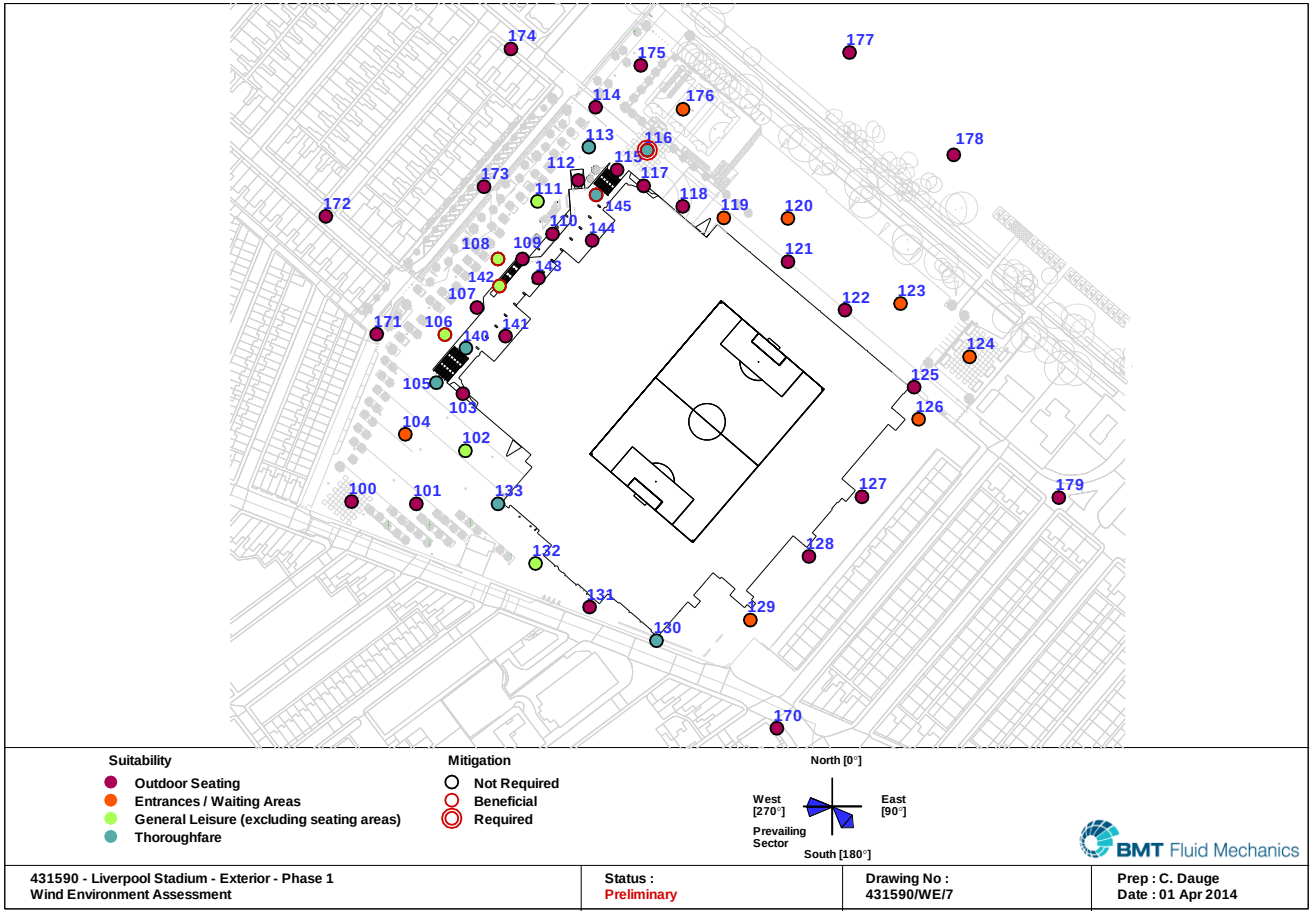
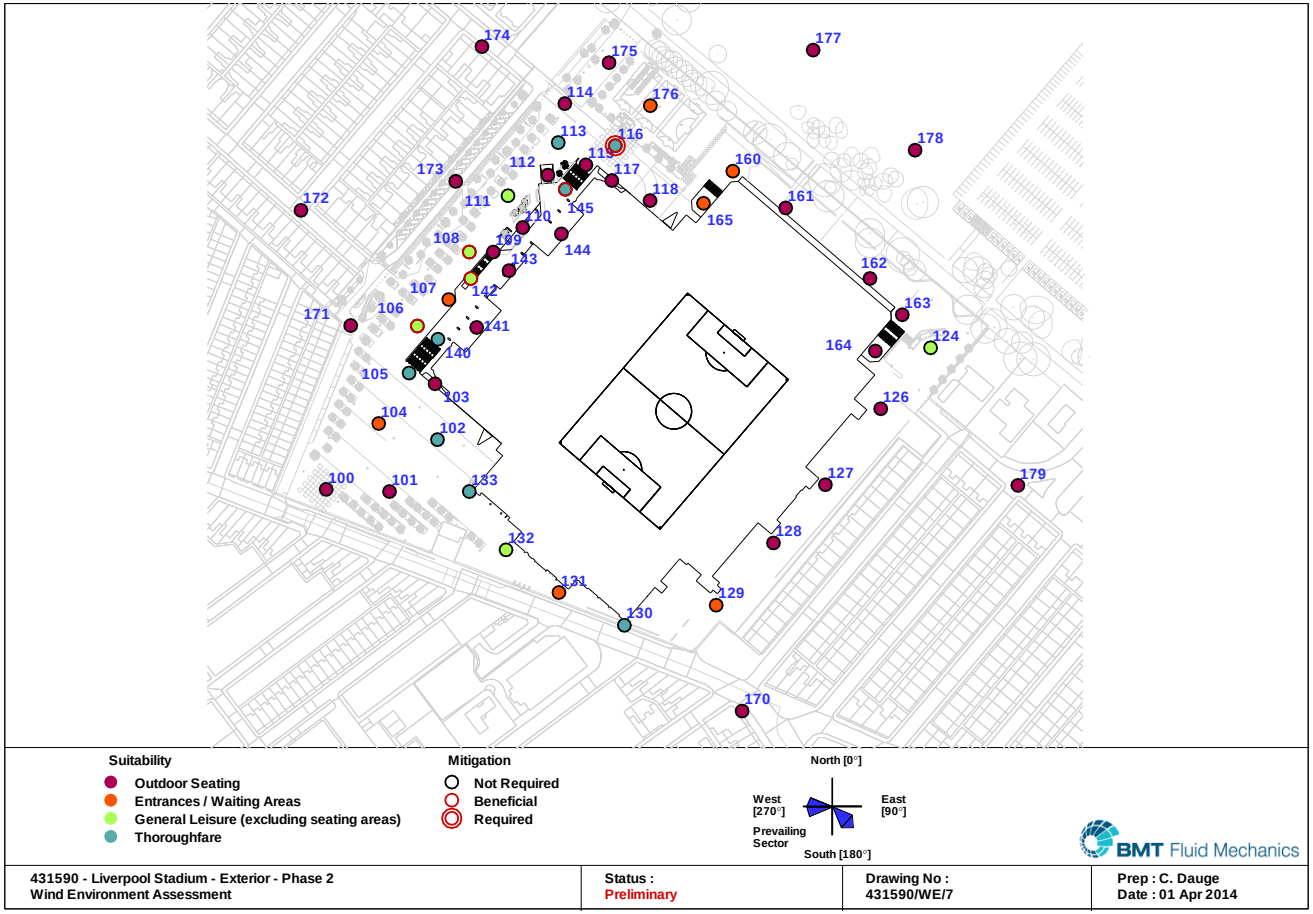


Figure 5.3: Pedestrian Level Wind Environment, Suitability Assessment: Phase 2 configuration



APPENDIX A. SPECIFICATION OF WIND CLIMATE

A.1. ESDU Wind Analysis

A detailed wind analysis was carried out to determine the wind properties at the site. The wind analysis is based on the widely accepted Deaves and Harris log law wind model of the atmospheric boundary layer, as defined in ESDU (Engineering Sciences Data Unit) Item 01008, and has provided wind profiles describing the variation of wind speed and turbulence intensity with height for a full range of wind directions. From this analysis representative profiles were defined as targets for the atmospheric boundary layer simulation in the wind tunnel.

A.1.1. Roughness Changes for ESDU Wind Analysis

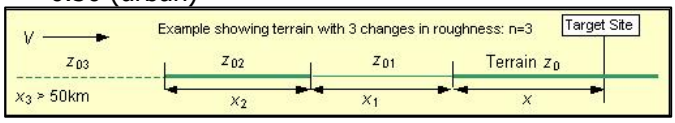
The wind analysis takes detailed account of the variation of the upwind terrain on each wind sector. The roughness changes used in the analysis for the current study are given in Table A.1 below.

Table A.1 - Terrain Roughness Changes from the Site

Wind Direction [deg]	z_0 [m]	x_0 [m]	z_{01} [m]	x01 [m]	z_{02} [m]	x02 [m]	z_{03} [m]	x03 [m]	z_{04} [m]	x04 [m]	z_{05} [m]
0	0.3	7,525	0.1	3,960	0.03						
30.0	0.3	7,525	0.03								
60.0	0.3	8,119	0.03	10,495	0.05	22,574	0.03				
90.0	0.3	6,931	0.08	15,248	0.03	17,228	0.3				
120.0	0.3	9,505	0.03								
150.0	0.3	12,871	water	2,970	0.03						
180.0	0.3	6,238	0.02	4,752	0.03						
210.0	0.3	1,188	0.5	2,970	water	2,376	0.3	3,168	0.02	12,871	0.03
240.0	0.3	1,089	0.5	2,178	water	990	0.2	11,881	water	7,129	0.03
270.0	0.3	1,980	0.5	990	water	1,782	0.3	3,762	water		
300.0	0.3	4,158	water								
330.0	0.3	9,109	0.03	5,545	0.05	3,960	water				

Where $\mathbf{x_0}$: upwind fetch
$\mathbf{z_0}$: roughness Groups length

N.B: $\mathbf{z_0}$ = water (sea)
0.03 (open terrain)
0.10 (sparsely built up suburban / country with trees)
0.30 (suburban)
0.50 (urban)



A.1.2. Wind Properties at Site

Figure A.1 shows the variation of turbulence intensity with wind direction at a height of 50m (considered the reference height for the proposed development). The target profile selected for the boundary layer simulation is that for 180°.

Figures A.2 and A.3 show the variation of mean wind-speed (normalised by the mean wind speed at the reference height of 50m) and turbulence with height for winds approaching the site from the four primary quarters.

Figure A.1 - Variation of Turbulence Intensity with Wind Direction at 50m Height, Including Reference Turbulence Levels

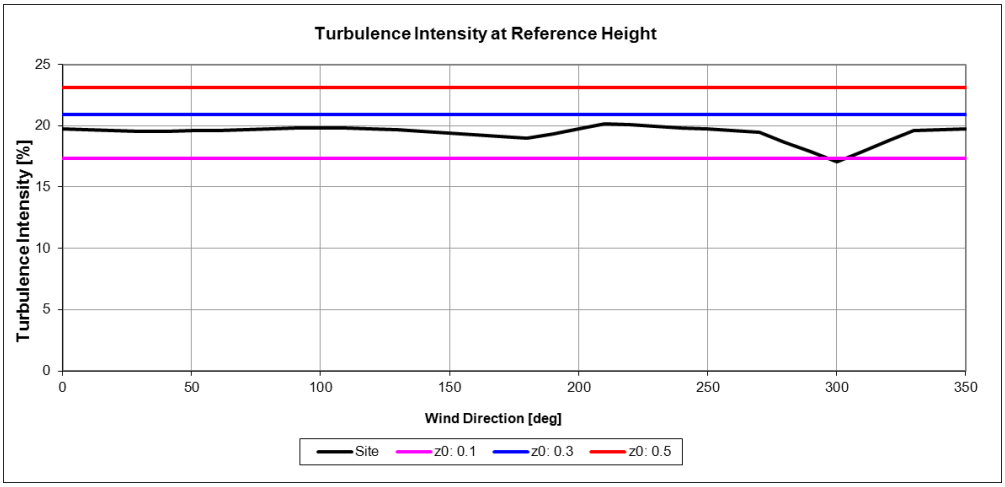


Figure A.2a - Mean Windspeed Profiles (normalised to reference height of 50m)

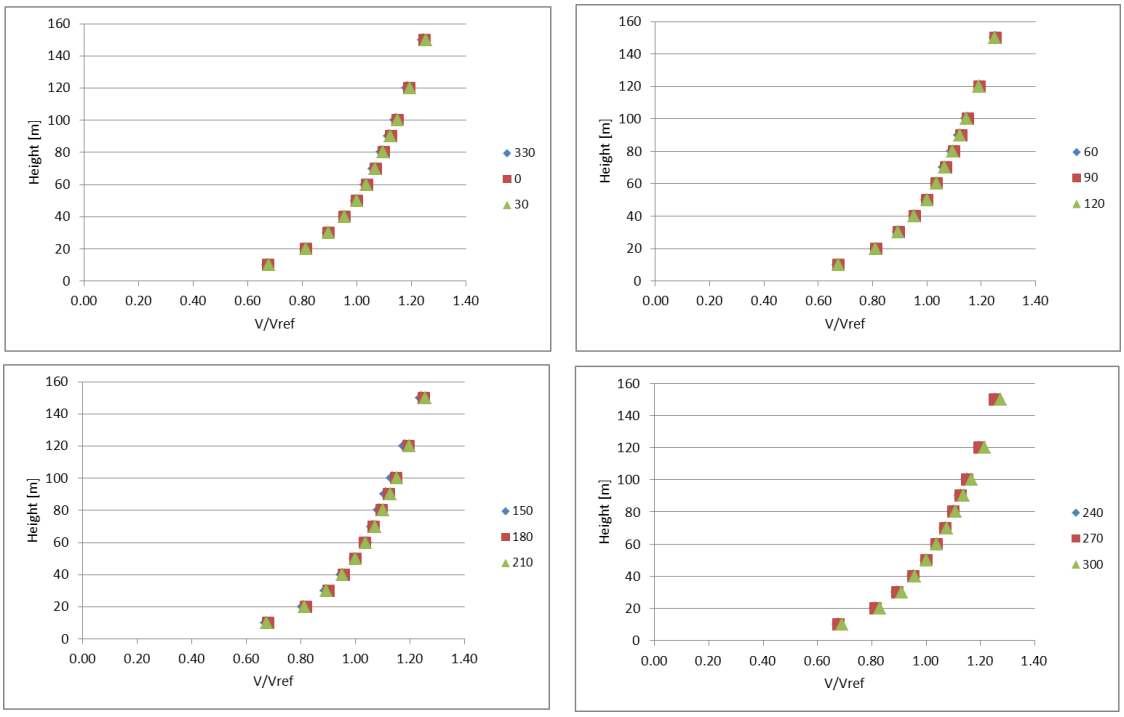
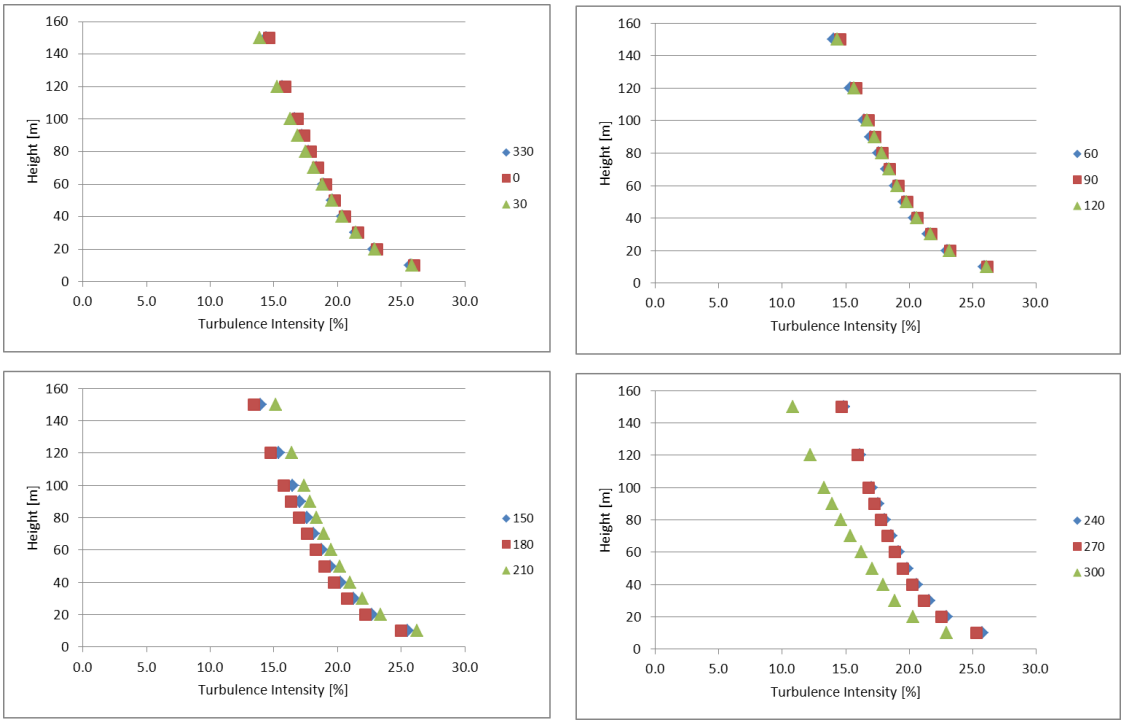


Figure A.3 - Turbulence Profiles



A.2. Wind Frequency Data

Wind environment studies require that wind speed data obtained from a measurement station be transposed to the site of interest.

The wind speed history, provided by weather centres such as the UK Met Office or the National Oceanic & Atmospheric Administration, is reformatted into the number of observations of mean hourly wind speeds within each of several wind speed ranges, for each wind direction and for each month of the year. To facilitate the transposition of the wind data, the months are grouped into the seasons and a Weibull distribution is fitted to the wind speed distribution for each wind direction, for each season.

From the Weibull cumulative distribution the probability that, for a given wind direction, a wind speed, V, will be exceeded is given by:

$$P(>V) = e^{-(\frac{V}{c})^k}$$

where c is the dispersion parameter and k is the shape parameter.

To these parameters is further added the probability, p, of each wind direction occurring. Thus for each month of the year the probability that a specified wind speed is exceeded for a specified wind direction may be calculated.

The resulting weather centre wind data is transposed to open country terrain at sea-level, accounting for upwind terrain, topography and altitude for the weather centre. The 50-year return period design wind speed is calculated based on the wind data and from comparison with the basic design wind speed specified in BS EN 1991-1-4:2005 for the weather centre area, local topography and/or proximity effects can be corrected for. Values of p, c and k for the Aughton Liverpool Weather Centre, transposed to open-country terrain at 10m height above sea-level altitude are given in the Table A.2.

The open country wind data is then transposed to reference height at the site of the proposed development, accounting for upwind terrain, topography and altitude for the target site. The resulting annual and seasonal directional and wind speed probability distributions at a reference height of 50m, at the proposed site, are given in Figures A.6 to A.8e, respectively.

Table A.2 - Wind Frequency Statistics: Aughton Weather Centre data transformed to z0=0.03m Weibull Coefficients

Annual	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
p	3.22	3.49	3.70	3.64	4.71	7.74	10.77	8.29	5.14	5.64	6.26	9.19	9.54	8.78	6.19	3.71
c	3.39	3.96	4.48	4.59	4.79	4.47	4.79	4.88	4.97	5.91	6.47	6.40	6.18	5.69	4.99	3.62
k	1.54	1.70	2.09	2.11	2.13	2.28	2.09	2.17	2.14	2.15	2.27	2.31	2.05	1.96	1.92	1.63

Autumn	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
p	4.25	3.88	4.29	3.17	4.67	8.89	13.64	9.43	5.51	5.16	4.88	7.28	8.14	7.47	5.28	4.05
c	3.63	3.80	4.06	3.85	4.55	4.47	4.57	4.58	4.77	5.33	5.92	6.14	6.09	5.96	4.93	3.60
k	2.22	1.89	1.86	1.88	2.42	2.61	1.94	2.14	2.29	2.20	2.47	2.35	2.16	2.00	1.83	1.78

Winter	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
p	2.72	3.22	3.03	3.42	4.83	9.07	13.58	9.60	6.08	7.13	7.85	9.64	7.97	5.03	3.53	3.28
c	3.31	3.95	4.45	4.95	5.20	4.81	5.33	5.34	5.72	6.96	7.57	7.73	7.84	6.88	5.46	4.08
k	1.27	1.50	2.05	2.11	2.03	2.18	2.35	2.22	2.28	2.38	2.51	2.51	2.29	1.93	1.73	1.59

Spring	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
p	3.09	3.59	4.57	4.82	5.33	7.23	9.25	7.90	4.42	5.21	6.30	9.38	9.51	8.78	6.86	3.76
c	4.16	4.49	5.16	5.09	4.96	4.61	5.02	5.23	4.89	6.06	6.65	6.63	6.28	5.80	5.32	3.99
k	1.86	1.85	2.34	2.44	2.39	2.48	2.23	2.33	2.19	2.30	2.41	2.47	2.32	2.19	2.01	1.93

Summer	0	22.5	45	67.5	90	112.5	135	157.5	180	202.5	225	247.5	270	292.5	315	337.5
p	2.82	3.27	2.90	3.12	3.97	5.79	6.64	6.21	4.50	4.98	5.90	10.40	12.58	14.01	9.17	3.75
c	2.92	3.71	3.82	4.06	4.52	3.87	3.76	4.22	4.35	4.78	5.19	5.13	5.13	5.12	4.66	2.95
k	1.79	1.89	2.17	2.21	2.42	2.42	2.15	2.52	2.30	2.18	2.13	2.40	2.56	2.38	2.36	1.57

Figure A.6 - Annual & Seasonal Directional Probability Distribution at Site

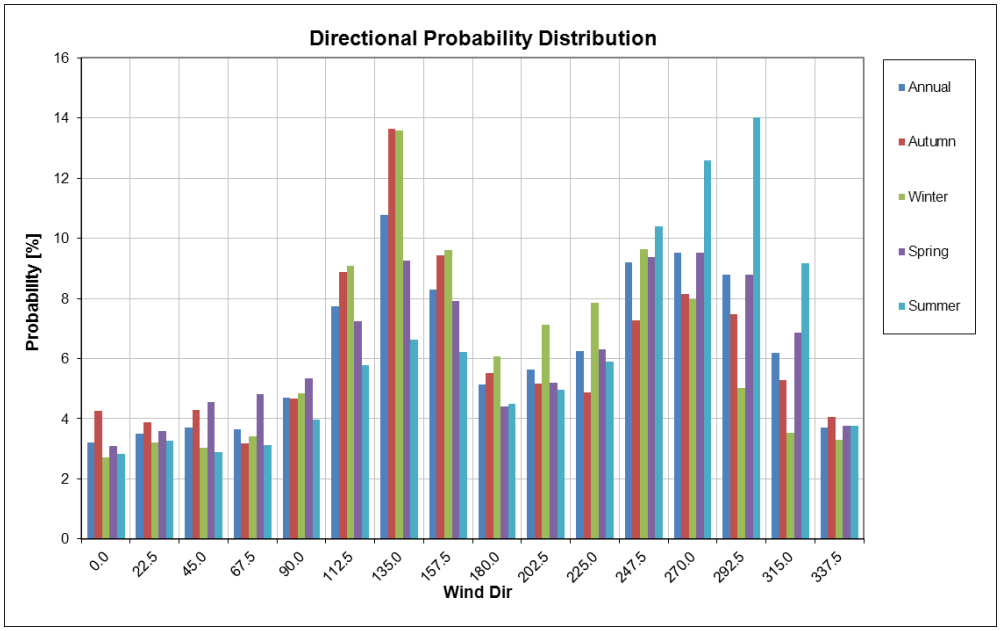


Figure A.7 - Annual & Seasonal Wind Speed Probability Distribution at Site (at 50m height)

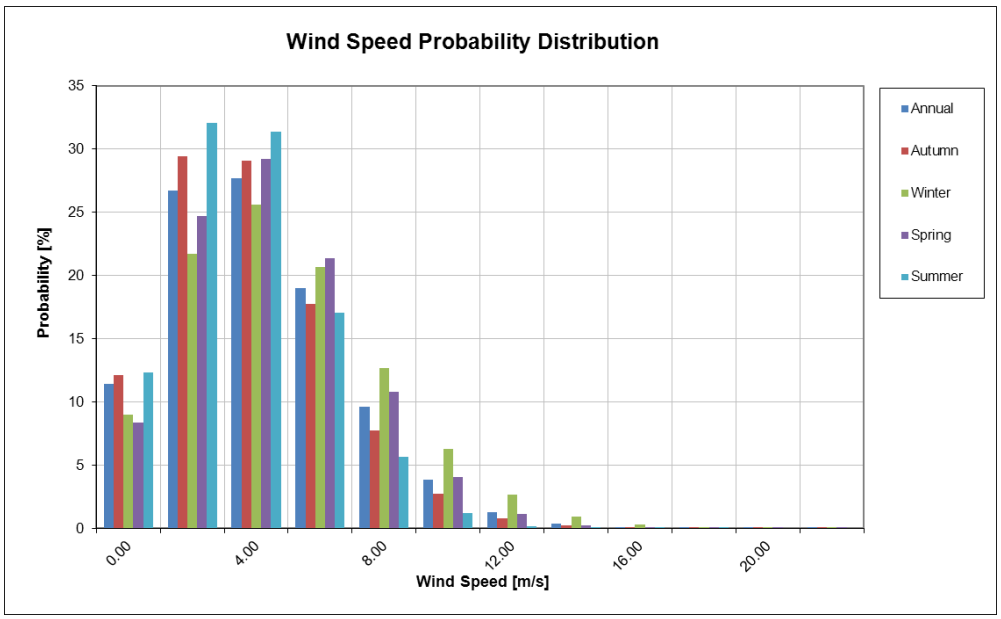


Figure A.8a - Directional Windspeed Probability Distribution at Site: Annual (at 50m height)

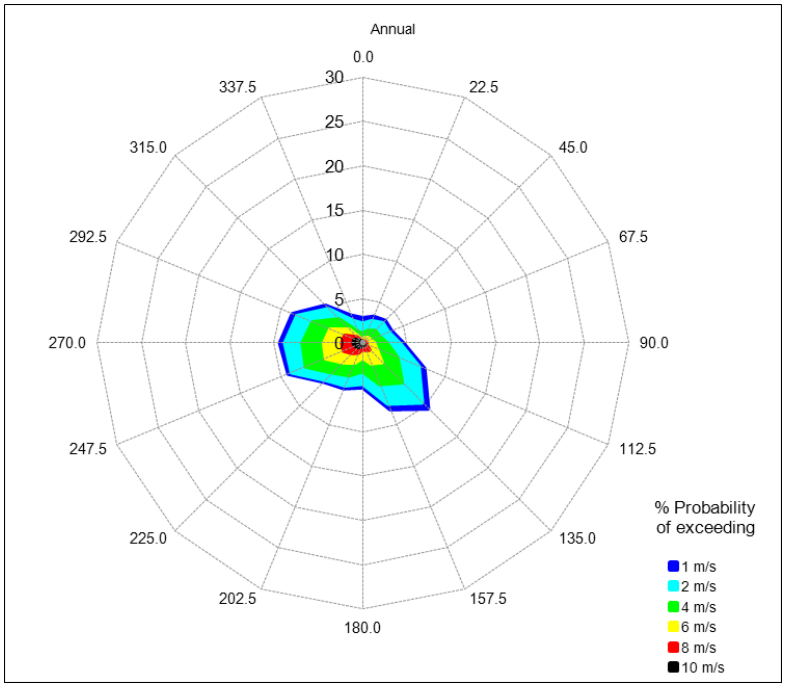


Figure A.8b - Directional Windspeed Probability Distribution at Site: Autumn (at 50m height)

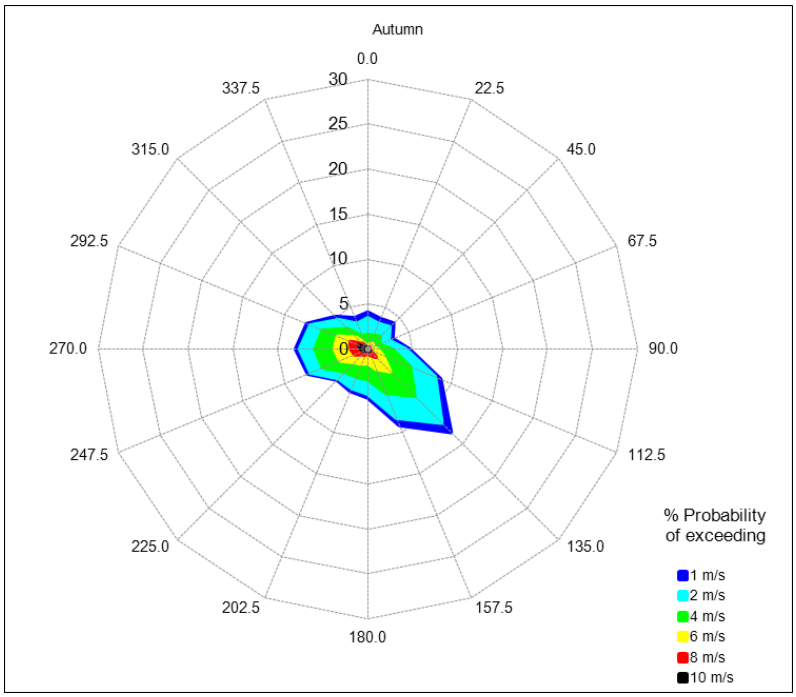


Figure A.8c - Directional Windspeed Probability Distribution at Site: Winter (at 50m height)

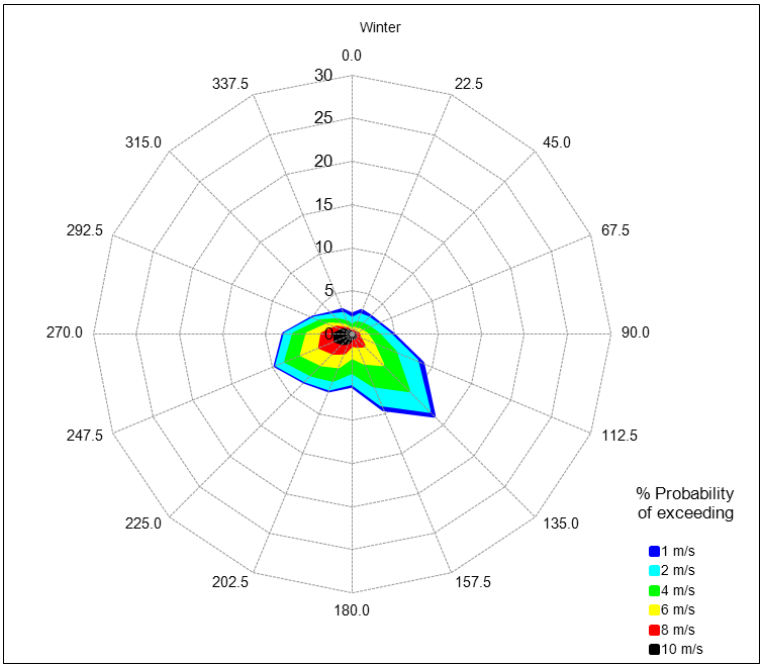


Figure A.8d - Directional Windspeed Probability Distribution at Site: Spring (at 50m height)

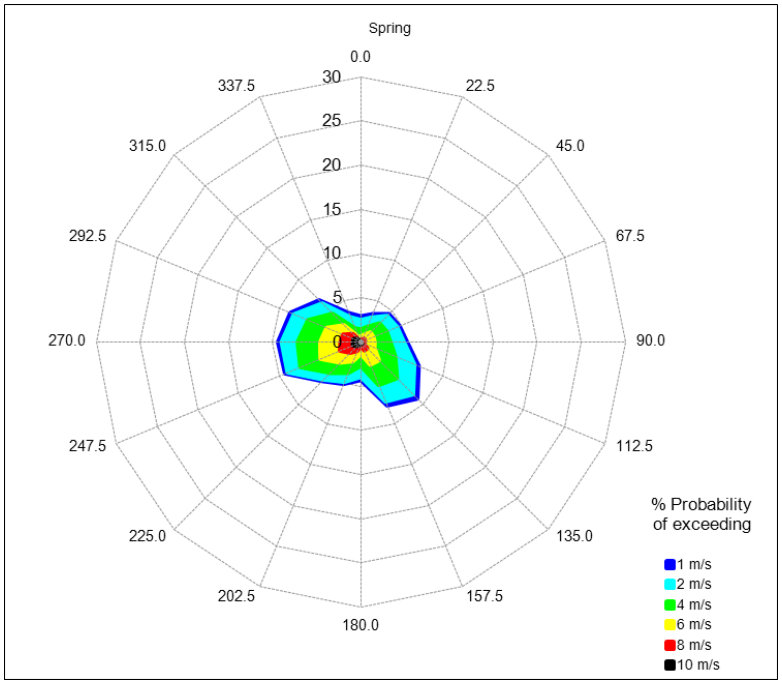
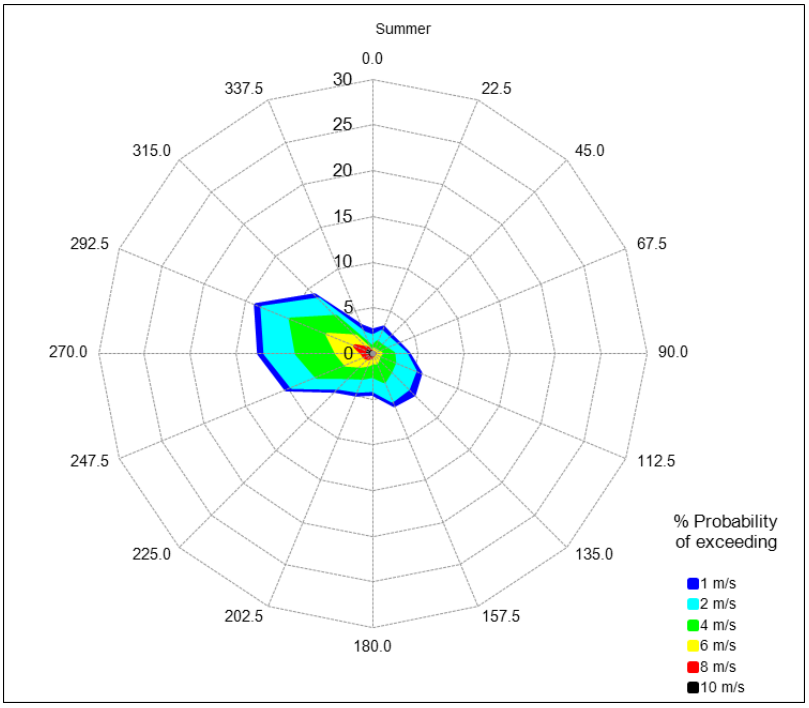


Figure A.8e - Directional Windspeed Probability Distribution at Site: Summer (at 50m height)



APPENDIX B. WIND TUNNEL & MODEL DETAILS

B.1. Wind Tunnel Specifications

All the tests were conducted in BMT's Boundary Layer Wind Tunnel which has a working section 4.8m wide, 2.4m high and 15m long with a 4.4m diameter multiple plate turntable and a remotely controlled 3-dimensional traversing system. The operating wind speed range is 0.2 – 45 m/s.

A turbulent boundary layer, representative of the conditions at the site, is set up using an arrangement of roughness elements distributed over the floor of the wind tunnel and a 2-dimensional barrier with square posts at the entrance to the test section.

Figure B.1 presents the profiles of mean wind speed and turbulence intensity, in the absence of the detailed wind tunnel model. The mean wind speed profile is normalised by the wind speed at a height of 50m. It can be seen that, over the range of heights of interest, the boundary layer simulation used in the tests was a good representation of that expected for the site at full scale.

B.2. Model

B.2.1. Information

The model of the proposed Anfield Extension Project was constructed based on drawing information supplied by KSS, the architect for the scheme, as follows:

Date	Drawing	Date	Drawing
03/03/2014	PL1312.GA.102 Phase 1 Stadium Concourse.dwg	03/03/2014	Liverpool Football Club - Floorplans - Second Floor Level.dwg
03/03/2014	12609-ARCHExistingStadium-Survey-mesh.dwg	03/03/2014	Liverpool Football Club - Floorplans First Floor Level.dwg
03/03/2014	12609-ARCHExistingStadium-Survey-solid.dwg	03/03/2014	LOWER TIER ANFIELD ROAD FLOOR PLAN - LIVERPOOL FOOTBALL CLUB.dwg
03/03/2014	08727_KL1 ANFIELD STADIUM.dwg	03/03/2014	MAIN STAND FLOOR PLAN-LIVERPOOL FOOTBALL CLUB.dwg
03/03/2014	08727_KL2 ANFIELD STADIUM.dwg	03/03/2014	ROOF PLAN - LIVERPOOL FOOTBALL CLUB, ANFIELD.dwg
03/03/2014	08727_KL3 ANFIELD STADIUM (Provisional).dwg	03/03/2014	UPPER TIER ANFIELD ROAD FLOOR PLAN - LIVERPOOL FOOTBALL CLUB.dwg
03/03/2014	08727_KL4 ANFIELD STADIUM.dwg	03/03/2014	PL564.S.100 revAexisting le.dwg

Date	Drawing	Date	Drawing
03/03/2014	08727_KL5 ANFIELD STADIUM.dwg	03/03/2014	08727-3dT-ANFIELD STADIUM LIVERPOOL REV A.dwg
03/03/2014	08727-E-01 ANFIELD ELEVATIONS.dwg	03/03/2014	38870390_1 .. 04B0L6537 _170512_Mesh.dwg
03/03/2014	08727-IE KOP ANFIELD STADIUM.dwg	03/03/2014	38870390_1 .. 04B0L6537 _170512_Solids.dwg
03/03/2014	08727-L1- CENTENARY STAND.dwg	07/03/2014	12609-ARCHMaster-Anfield Road Stand.dwg
03/03/2014	08727-L2-CENTENARY STAND.dwg	07/03/2014	12609-ARCHMaster-Main stand.dwg
03/03/2014	08727-L3-CENTENARY STAND.dwg	07/03/2014	12609-ExistingStadiumSurvey.dwg
03/03/2014	08727-L4-CENTENARY STAND.dwg	07/03/2014	12609-ARCHMaster.dwg
03/03/2014	08727-L5-CENTENARY STAND.dwg	07/03/2014	12609-ARCH Master.dwg
03/03/2014	ELEVATIONS - LIVERPOOL FOOTBALL CLUB.dwg	11/03/2014	PL1312.LFC Stage D Phase 1 Masterplan.dwg
03/03/2014	Liverpool Football Club - Floorplans - Ground Floor Level.dwg	11/03/2014	PL1312.LFC Stage D Phase 2 Masterplan.dwg

The model of the existing surrounding area was based on OS superplan data supplemented by a site survey conducted by BMT.

The models of the consented future surrounding development were based on documentation sourced from the public domain.

B.2.2. Scale

A model scale of 1:250 has been adopted. At this scale the model is large enough to allow a good representation of the details that are likely to affect the local and overall wind flows at full scale. In addition, this scale enables a good simulation of the turbulence properties of the wind to be achieved.

B.2.3. Construction

The model was constructed from a combination of materials such as hard foam, wood and perspex. The model incorporated all of the features that are likely to significantly affect the local wind flow around the development at full scale. The surrounding area was modelled to a radius of 550m from the

centre of the site. The surrounding buildings and topography were represented to a sufficient level of detail to reproduce the wind flows at the location of the proposed development. Mature existing trees were represented in winter, or bare, format.

The model was mounted on the 4.4m diameter turntable of BMT's Boundary Layer Wind Tunnel.

B.2.4. Model Photos

Images of the wind tunnel model are presented as follows:

- Figure B.2: Existing Configuration
- Figure B.3: Phase 1 with New Main Stand // Close up view
- Figure B.4: Phase 2 with New Main Stand and New Anfield Stand // Close up view

Figure B.1 - Mean wind speed ($V_{mean}/V_{mean(ref)}$), turbulence intensity profile (I_u) and gust wind speed ($V_{gust}/V_{mean(ref))}$ used in the study

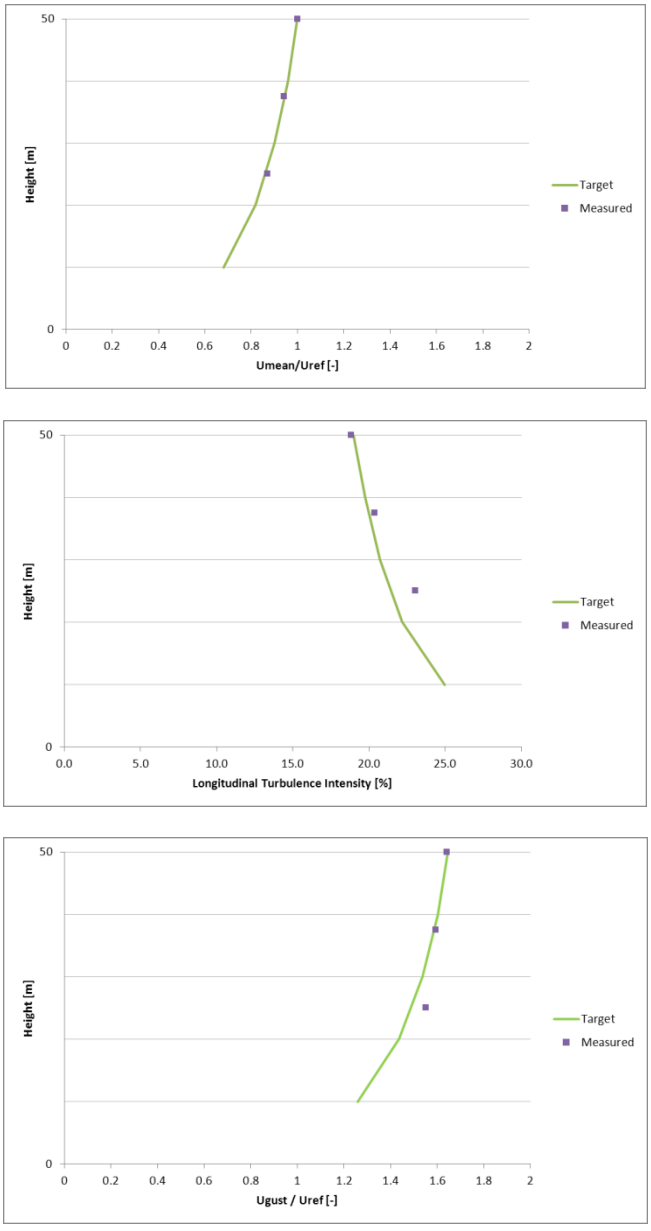
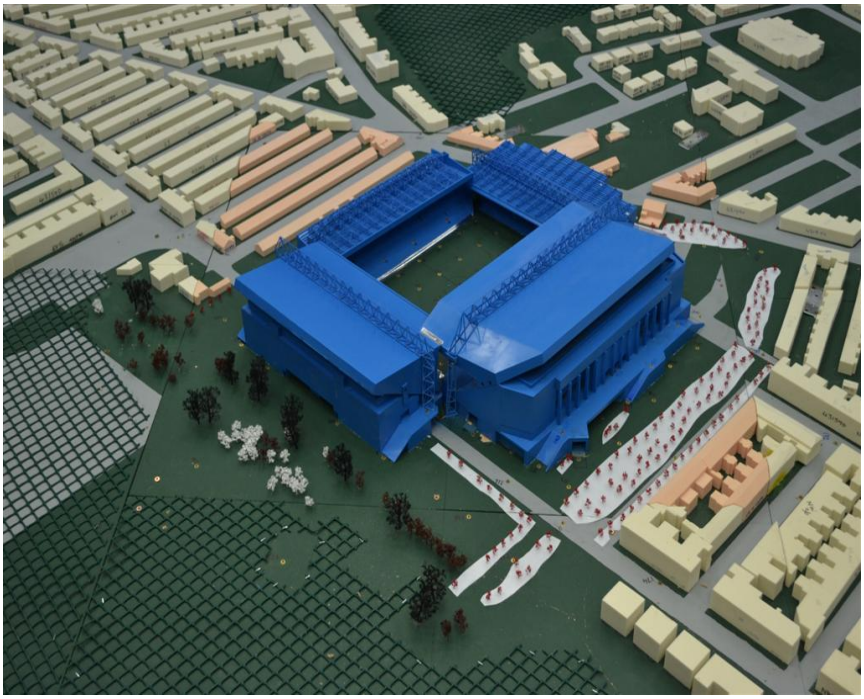


Figure B.2 - Existing Configuration

Figure B.3 - Phase 1 with the New Main Stand, Close up view

Figure B.4 - Phase 2 with New Anfield Stand, Close up view



APPENDIX C. MEASUREMENTS AND ANALYSIS

C.1. Physical Measurements

Wind speed measurements were made using so-called 'Irwin probes', capable of measuring fluctuating pressure differences that are calibrated against wind speed. A system of probes running simultaneously was used to obtain results from up to 50 locations at a height corresponding to 1.5m at full scale. Measurements were taken for a full range of wind directions in increments of 22.5°.

Data were recorded for a sufficient length of time to determine the mean and 3-second gust wind speeds.

Gusts in the wind flow may lead to additional discomfort beyond that caused by the mean wind speed. In order to assess this discomfort the gust wind speed is translated to an equivalent mean wind speed, the Gust Equivalent Mean or GEM, according to the following equation:

$$U_{GEM} = \frac{U_{GUST}}{1.85}$$

For each location the results were combined with local wind statistics to assess the wind environment in terms of the exceedance of threshold wind speeds that relate to comfort levels perceived during standard pedestrian activities.

C.2. Assessment Criteria

The widely accepted, UK industry standard, Lawson criteria for pedestrian comfort and safety are applied in the study.

Details of the comfort criteria are presented in Table C.1 and are based on the exceedance of the threshold wind speeds, based on the mean hourly value and on the gust equivalent mean value, occurring less than 5% of the time. The value of 5% has been established as giving a reasonable allowance for extreme and relatively infrequent winds that are tolerable within each category.

Table C.1 - Pedestrian Comfort Criteria

Threshold Mean-hourly Wind Speed Exceeded < 5% of the Time	Comfort Rating / Activity		Qualifying Comments
4m/s	C4	Long term sitting	Reading a newspaper and eating and drinking
6m/s	C3	Standing or short term sitting	Appropriate for bus stops, window shopping and building entrances
8m/s	C2	Walking or strolling	General areas of walking and sightseeing
10m/s	C1	Business walking	Local areas around tall buildings where people are not likely to linger
> 10m/s	C0	Uncomfortable	Uncomfortable for all pedestrian activities

Details of the safety criteria are presented in Table C.2 and are based on the exceedance of the threshold wind speeds, based on the mean hourly value and on the gust equivalent mean value, occurring once per annum. A wind speed greater than 15 metres-per-second occurring once a year is classified as unsuitable for general public and represents a wind speed with the potential to destabilise the less able members of the public such as the elderly, cyclists and children. Able-bodied users are those determined to experience distress when the wind speed exceeds 20 metres-per-second once per year.

Table C.2 - Pedestrian Safety Criteria

Threshold Mean-hourly Wind Speed Exceeded Once per Annum	Safety Rating		Qualifying Comments
> 15 m/s	S2	Unsuitable for general public	Less able and cyclists find conditions physically difficult
> 20 m/s	S1	Unsuitable for able-bodied	Able-bodied persons find conditions difficult. Physically impossible to remain standing during gusts.

C.3. Pedestrian Activities

Table C.3 to C.6 presents the pedestrian uses assumed for each configuration for each of the corresponding measurement locations presented in Figures 5.1 to 5.3.

Table C.3 - Existing configuration, Pedestrian Use.

Locn	Use	Locn	Use
100	Thoroughfare (mixed-use/residential)	127	Thoroughfare (mixed-use/residential)
101	Thoroughfare (mixed-use/residential)	128	Thoroughfare (mixed-use/residential)
102	Thoroughfare (mixed-use/residential)	129	Thoroughfare (mixed-use/residential)
104	Thoroughfare (mixed-use/residential)	130	Thoroughfare (mixed-use/residential)
105	Thoroughfare (mixed-use/residential)	131	Thoroughfare (mixed-use/residential)
106	Thoroughfare (mixed-use/residential)	132	Thoroughfare (mixed-use/residential)
107	Thoroughfare (mixed-use/residential)	133	Thoroughfare (mixed-use/residential)
108	Thoroughfare (mixed-use/residential)	150	Thoroughfare (mixed-use/residential)
109	Thoroughfare (mixed-use/residential)	151	Thoroughfare (mixed-use/residential)
110	Thoroughfare (mixed-use/residential)	152	Thoroughfare (mixed-use/residential)
111	Thoroughfare (mixed-use/residential)	153	Entrances
112	Thoroughfare (mixed-use/residential)	154	Entrances
113	Thoroughfare (mixed-use/residential)	155	Entrances
114	Thoroughfare (mixed-use/residential)	156	Thoroughfare (mixed-use/residential)
115	Thoroughfare (mixed-use/residential)	157	Thoroughfare (mixed-use/residential)
116	Thoroughfare (mixed-use/residential)	170	Thoroughfare (mixed-use/residential)
117	Thoroughfare (mixed-use/residential)	171	Thoroughfare (mixed-use/residential)
119	Thoroughfare (mixed-use/residential)	172	Thoroughfare (mixed-use/residential)
120	Thoroughfare (mixed-use/residential)	173	Thoroughfare (mixed-use/residential)
121	Thoroughfare (mixed-use/residential)	174	Thoroughfare (mixed-use/residential)
122	Thoroughfare (mixed-use/residential)	175	Thoroughfare (mixed-use/residential)
123	Thoroughfare (mixed-use/residential)	176	Thoroughfare (mixed-use/residential)
124	Thoroughfare (mixed-use/residential)	177	Thoroughfare (mixed-use/residential)
125	Thoroughfare (mixed-use/residential)	178	Thoroughfare (mixed-use/residential)
126	Thoroughfare (mixed-use/residential)	179	Thoroughfare (mixed-use/residential)

Table C.4 - Phase 1, Pedestrian Use.

Locn	Use	Locn	Use
100	Thoroughfare (mixed-use/residential)	125	Thoroughfare (mixed-use/residential)
101	Thoroughfare (mixed-use/residential)	126	Thoroughfare (mixed-use/residential)
102	Thoroughfare (mixed-use/residential)	127	Thoroughfare (mixed-use/residential)
103	Entrances	128	Thoroughfare (mixed-use/residential)
104	Thoroughfare (mixed-use/residential)	129	Thoroughfare (mixed-use/residential)
105	Thoroughfare (mixed-use/residential)	130	Thoroughfare (mixed-use/residential)
106	Recreational Space (no seating)	131	Thoroughfare (mixed-use/residential)
107	Recreational Space (no seating)	132	Thoroughfare (mixed-use/residential)
108	Recreational Space (no seating)	133	Thoroughfare (mixed-use/residential)
109	Thoroughfare (mixed-use/residential)	140	Thoroughfare (mixed-use/residential)
110	Entrances	141	Entrances
111	Thoroughfare (mixed-use/residential)	142	Recreational Space (no seating)
112	Thoroughfare (mixed-use/residential)	143	Entrances
113	Thoroughfare (mixed-use/residential)	144	Thoroughfare (mixed-use/residential)
114	Thoroughfare (mixed-use/residential)	145	Thoroughfare (mixed-use/residential)
115	Thoroughfare (mixed-use/residential)	170	Thoroughfare (mixed-use/residential)
116	Recreational Space (no seating)	171	Thoroughfare (mixed-use/residential)
117	Entrances	172	Thoroughfare (mixed-use/residential)
118	Thoroughfare (mixed-use/residential)	173	Recreational Space (no seating)
119	Thoroughfare (mixed-use/residential)	174	Thoroughfare (mixed-use/residential)
120	Thoroughfare (mixed-use/residential)	175	Recreational Space (no seating)
121	Thoroughfare (mixed-use/residential)	176	Recreational Space (no seating)
122	Thoroughfare (mixed-use/residential)	177	Thoroughfare (mixed-use/residential)
123	Thoroughfare (mixed-use/residential)	178	Thoroughfare (mixed-use/residential)
124	Recreational Space (no seating)	179	Thoroughfare (mixed-use/residential)

Table C.5 - Phase 2, Pedestrian Use.

Locn	Use	Locn	Use
100	Thoroughfare (mixed-use/residential)	131	Thoroughfare (mixed-use/residential)
101	Thoroughfare (mixed-use/residential)	132	Thoroughfare (mixed-use/residential)
102	Thoroughfare (mixed-use/residential)	133	Thoroughfare (mixed-use/residential)
103	Entrances	140	Thoroughfare (mixed-use/residential)
104	Thoroughfare (mixed-use/residential)	141	Entrances
105	Thoroughfare (mixed-use/residential)	142	Recreational Space (no seating)
106	Recreational Space (no seating)	143	Entrances
107	Recreational Space (no seating)	144	Entrances
108	Recreational Space (no seating)	145	Thoroughfare (mixed-use/residential)
109	Thoroughfare (mixed-use/residential)	160	Thoroughfare (mixed-use/residential)
110	Entrances	161	Thoroughfare (mixed-use/residential)
111	Thoroughfare (mixed-use/residential)	162	Thoroughfare (mixed-use/residential)
112	Thoroughfare (mixed-use/residential)	163	Thoroughfare (mixed-use/residential)
113	Thoroughfare (mixed-use/residential)	164	Entrances
114	Thoroughfare (mixed-use/residential)	165	Entrances
115	Thoroughfare (mixed-use/residential)	170	Thoroughfare (mixed-use/residential)
116	Recreational Space (no seating)	171	Thoroughfare (mixed-use/residential)
117	Entrances	172	Thoroughfare (mixed-use/residential)
118	Thoroughfare (mixed-use/residential)	173	Recreational Space (no seating)
124	Thoroughfare (mixed-use/residential)	174	Thoroughfare (mixed-use/residential)
126	Thoroughfare (mixed-use/residential)	175	Recreational Space (no seating)
127	Thoroughfare (mixed-use/residential)	176	Recreational Space (no seating)
128	Thoroughfare (mixed-use/residential)	177	Thoroughfare (mixed-use/residential)
129	Thoroughfare (mixed-use/residential)	178	Thoroughfare (mixed-use/residential)
130	Thoroughfare (mixed-use/residential)	179	Thoroughfare (mixed-use/residential)

APPENDIX D. COMFORT AND SAFETY CRITERIA

The results of the pedestrian level wind speed measurements are summarised in graphical format in terms of comfort and safety criteria derived for each measurement location and presented, as follows:

- Figures D.1a to D.1c presents **Summer season** ratings at for each configuration
- Figures D.2a to D.2c presents **Worst seasonal** ratings for each configuration
- Figures D.3a to D.3C presents **Annual Comfort** ratings for each configuration

The presentations listed above show the worst case between the results derived using wind speed-up factors based on the mean and gust equivalent mean (GEM) wind speeds.

Figure D.1a - Pedestrian Level Wind Environment – Summer Comfort and Safety Ratings: Existing configuration

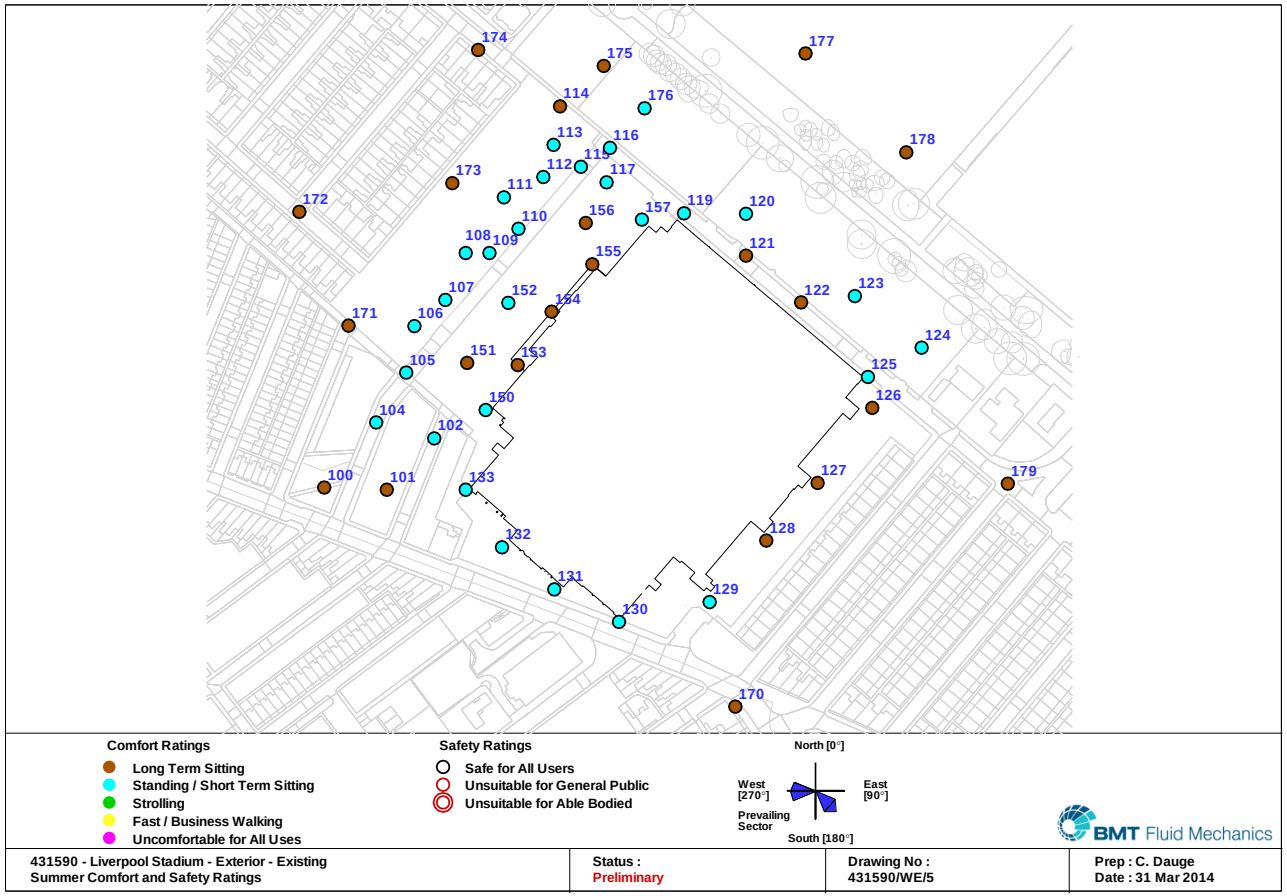


Figure D.1b - Pedestrian Level Wind Environment – Summer Comfort and Safety Ratings: Phase 1

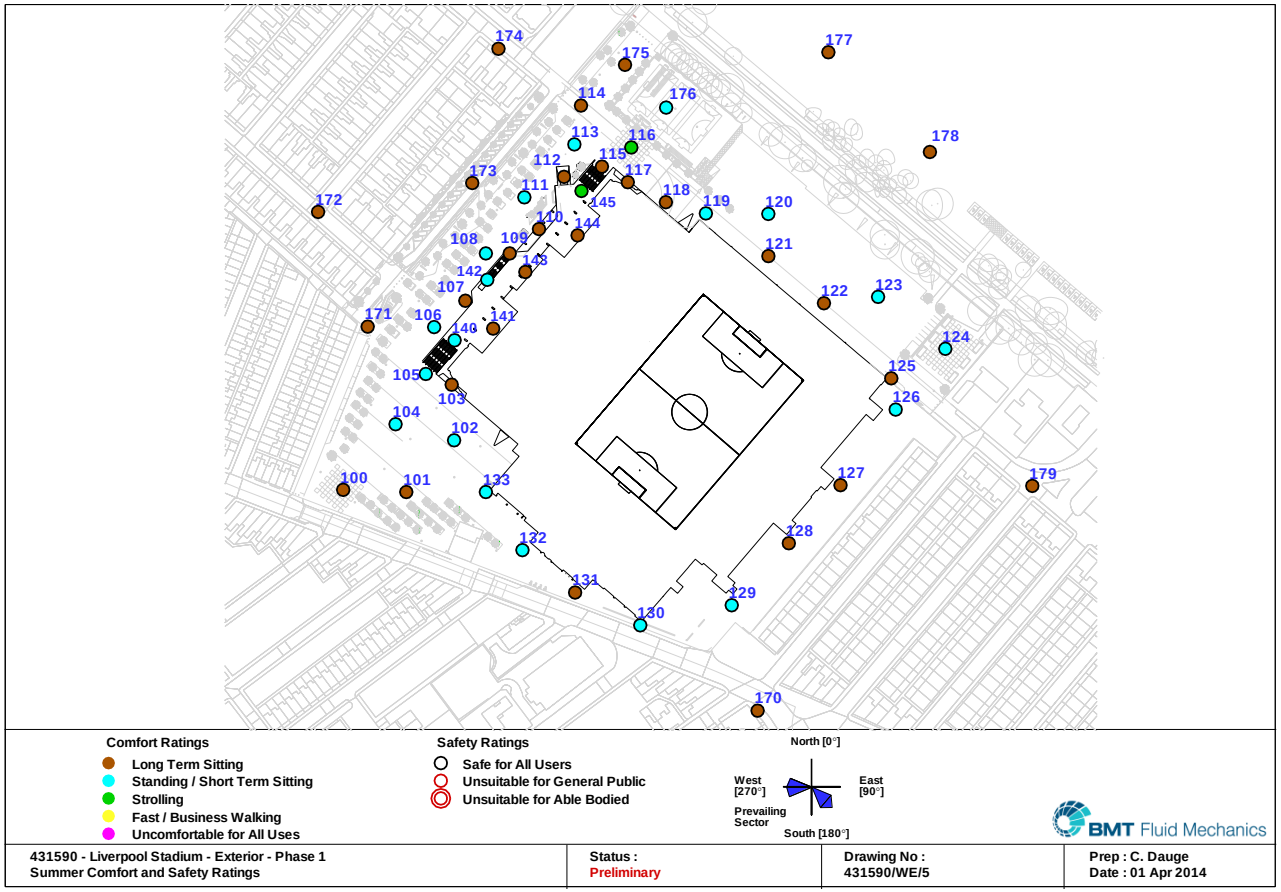


Figure D.1c - Pedestrian Level Wind Environment – Summer Comfort and Safety Ratings: Phase 2

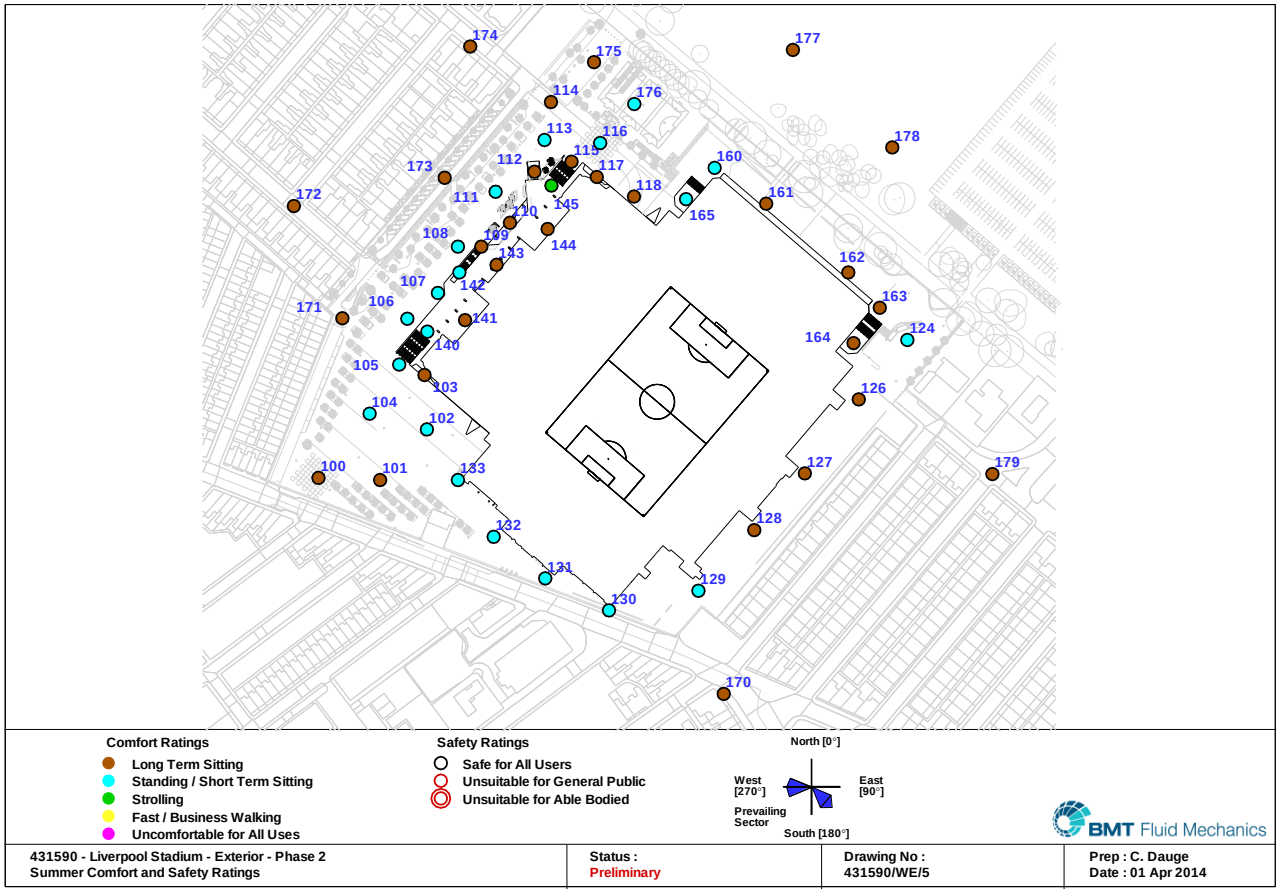


Figure D.2a - Pedestrian Level Wind Environment – Worst Seasonal Comfort and Safety Ratings: Existing Configuration

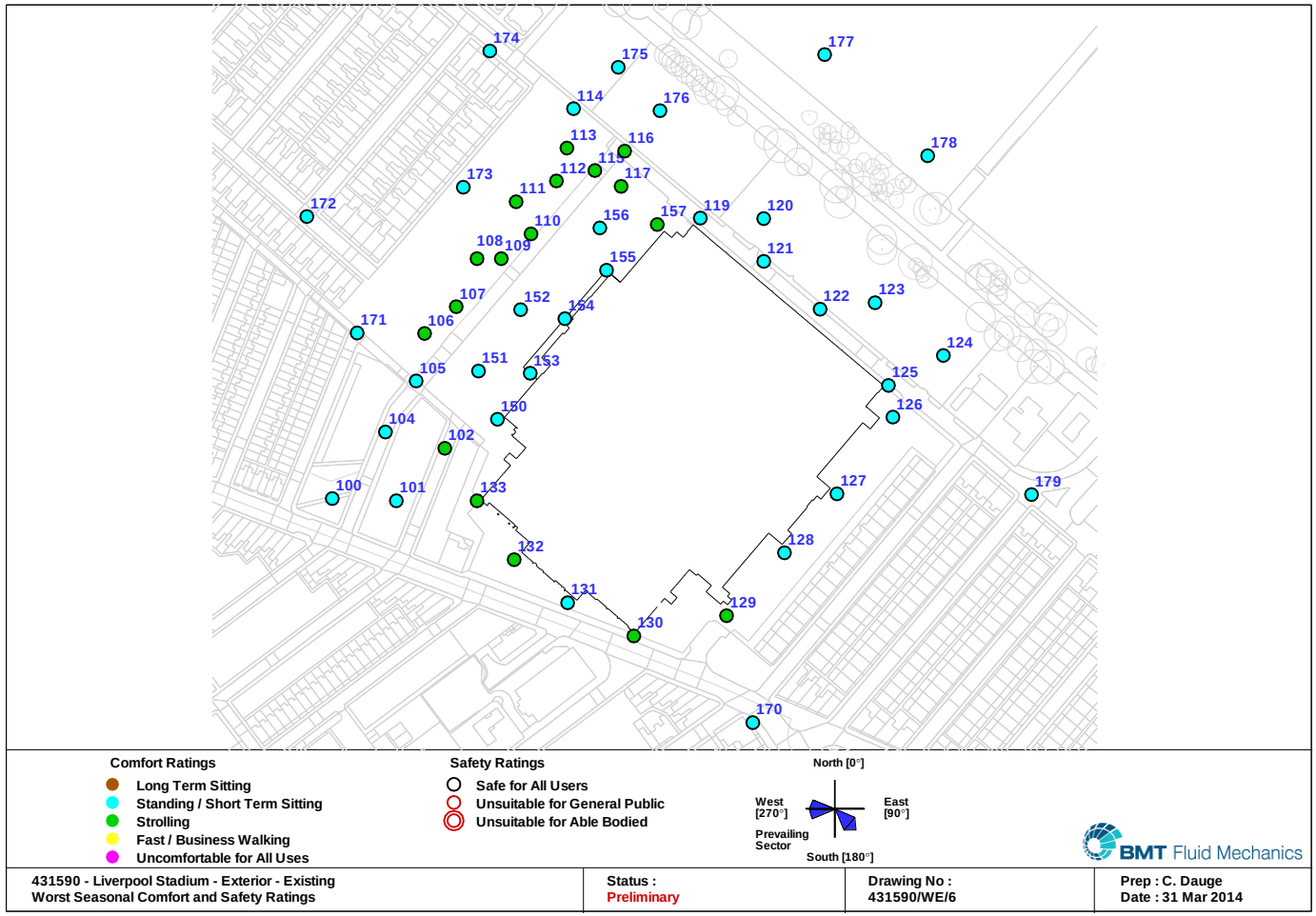


Figure D.2b - Pedestrian Level Wind Environment – Worst Seasonal Comfort and Safety Ratings: Phase 1

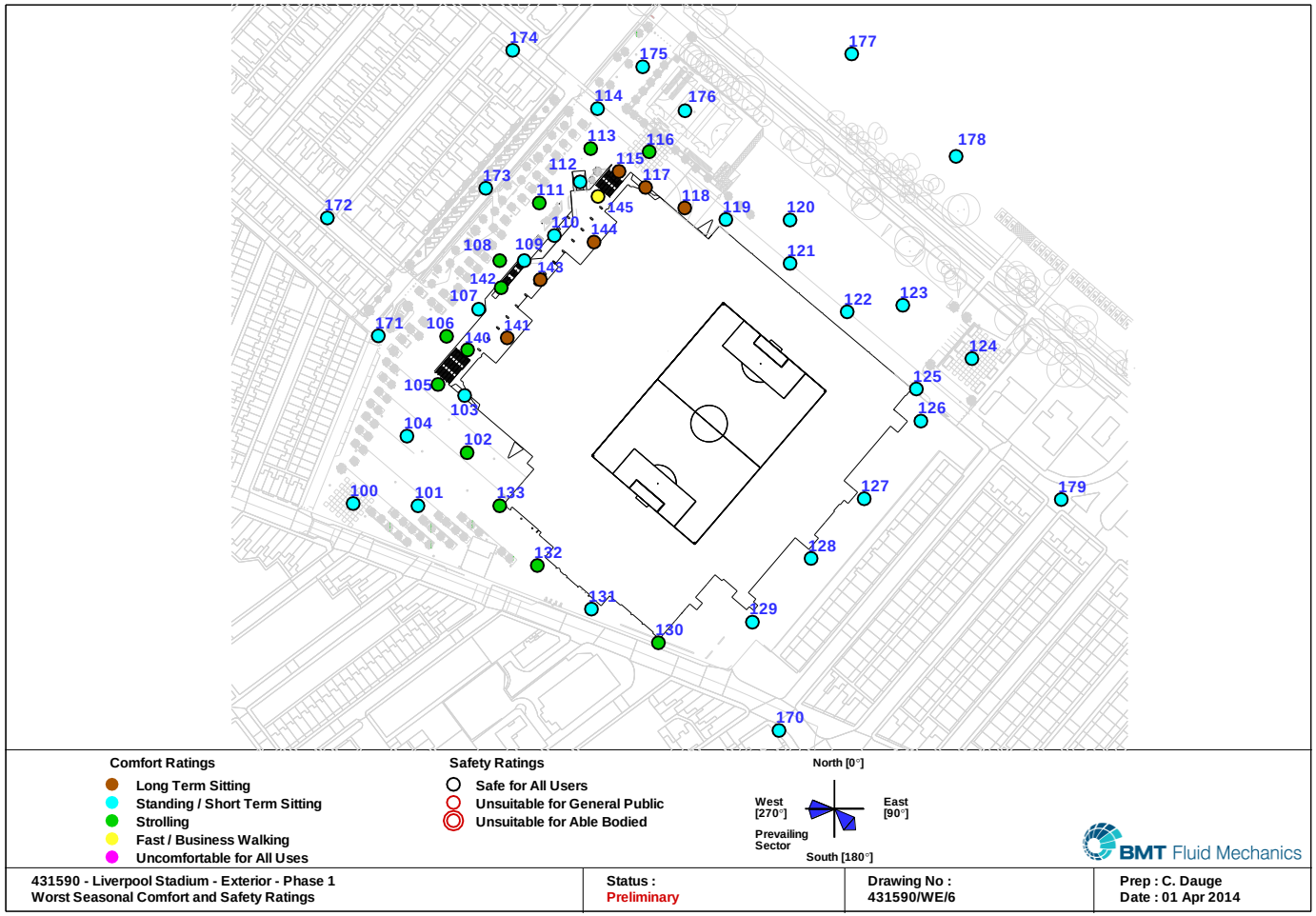


Figure D.2c - Pedestrian Level Wind Environment – Worst Seasonal Comfort and Safety Ratings: Phase 2

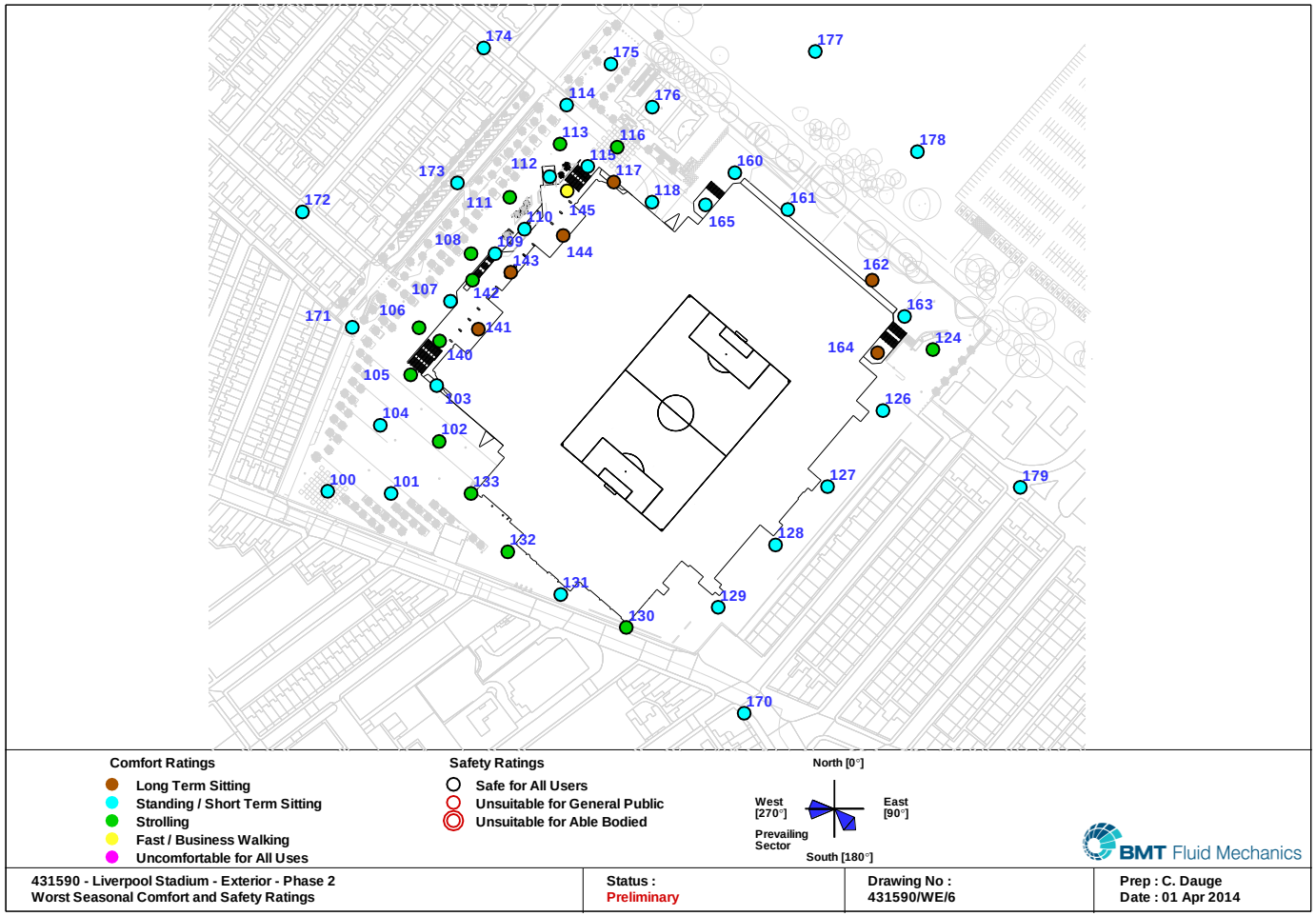


Figure D.3a - Pedestrian Level Wind Environment – Annual Comfort: Existing Configuration

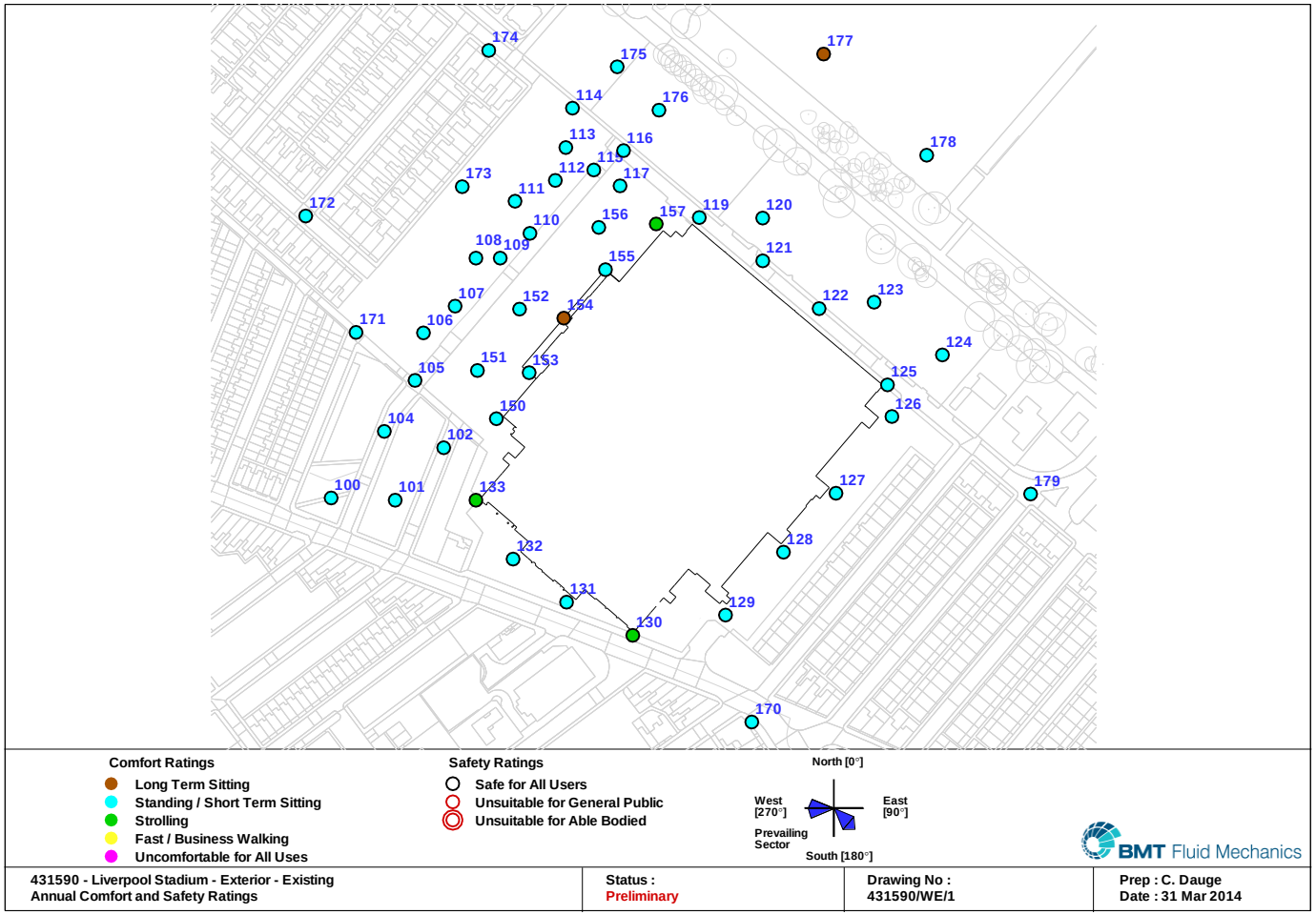


Figure D.3b - Pedestrian Level Wind Environment – Annual Comfort: Phase 1

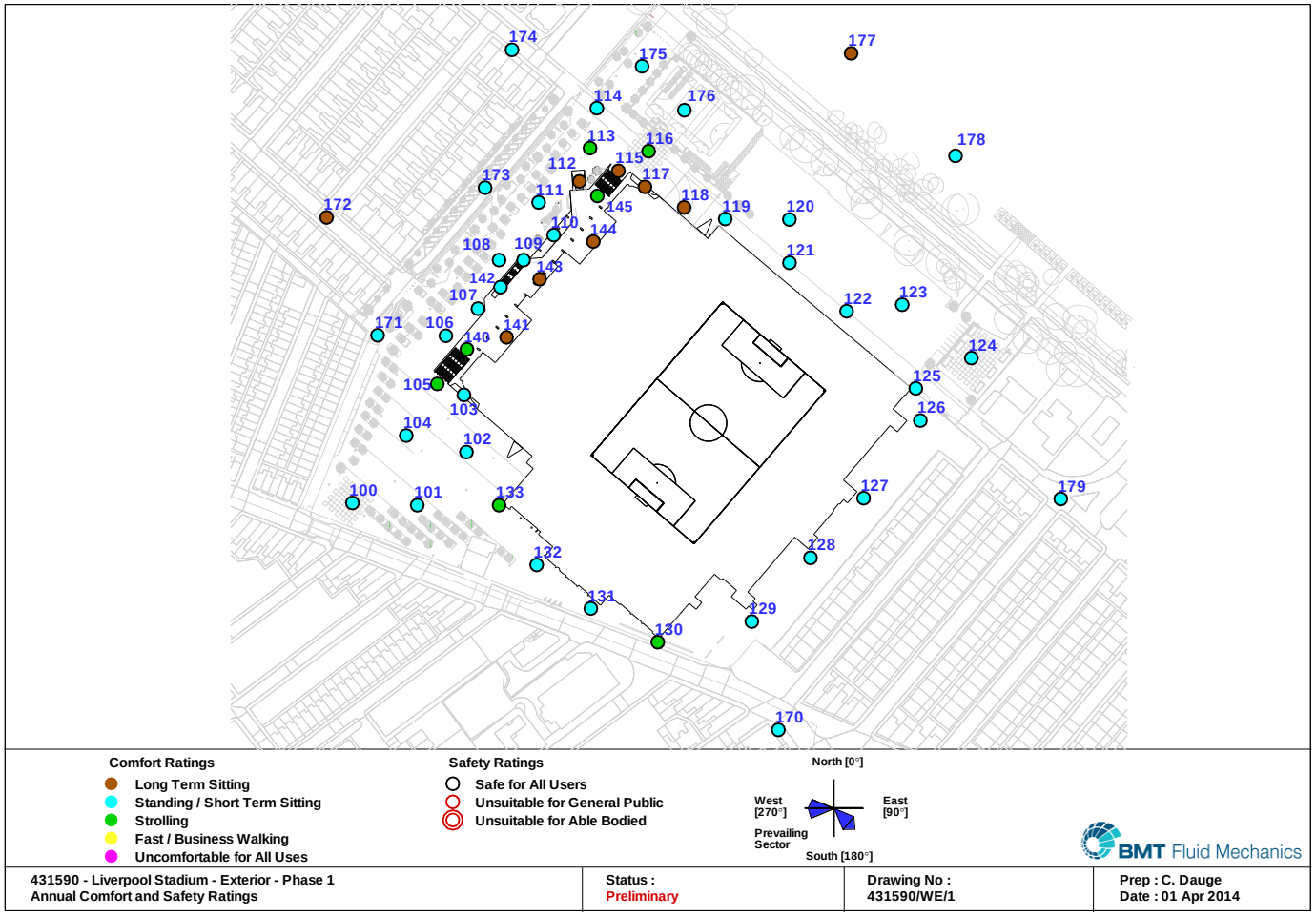


Figure D.3c - Pedestrian Level Wind Environment – Annual Comfort: Phase 2