DRAFT REPORT

# CAUSEWAY PEDESTRIAN BRIDGES

PERTH, WESTERN AUSTRALIA

## WIND CLIMATE AND SITE EXPOSUE REPORT

RWDI #2100795

September 5, 2022


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# EXECUTIVE SUMMARY

A wind climate and site exposure study has been performed for the Causeway Pedestrian Bridges - Point Fraser Bridge and McCallum Park Bridge in Perth, Western Australia. The following represents a summary of the key findings in the current study:

- A Climatological Analysis has been carried out to establish critical wind conditions at the bridge sites as required for design. The study also recommended appropriate turbulence properties relevant for the derivation of design wind loads. These speeds are based on RWDI's extreme value analysis and indicate good consistency with AS/NZS 1170.2:2021 values.
- Recommended wind speeds for design of the completed bridge and during construction are provided for strength and stability in Table 2.1a to Table 2.1d, and turbulence properties are provided in Table 2.2a and Table 2.2b.
- These recommendations are based on preliminary information about the bridge locations, deck height and alignment as provided to RWDI. Any changes to this information may require revision of these values.

Additional detailed studies of the wind loads on the bridge are to follow.

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# VERSION HISTORY

| RWDI Project #2100975 | Wind Engineering Services | |
|---|---|---|
| **Report** | **Releases** | **Date** |
| **Wind Climate and Site Exposure Report** | First Draft | September 5, 2022 |

# 1 INTRODUCTION

RWDI Australia Pty Ltd (RWDI) was retained by the Causeway Link Alliance to undertake comprehensive wind engineering studies for the Causeway Pedestrian Bridges (Point Fraser Bridge and McCallum Park Bridge) in Perth, Western Australia. This report presents the preliminary wind climate and site exposure study results and recommendations

## 1.1 Project Description

The proposed bridges span the Swan River approximately 80-90 m downstream of the existing Causeway Bridges, in the vicinity of the Perth CBD in Western Australia. The proposed design consists of two cable-stayed bridges with two pylons for the McCallum Park Bridge and one pylon for the Point Fraser Bridge. Their location is shown in Figure 2-1. Based on the information provided, this assessment assumes a deck elevation of approximately 8m and an alignment of 140-320 degrees for both Point Fraser Bridge and McCallum Park Bridge.

## 1.2 Objectives

The wind engineering services presented in this report include the wind climate assessment and site exposure of the proposed bridge location, which provides the site-specific design wind speeds and turbulence properties for design and stability verifications.

# 2 CLIMATOLOGY ANALYSIS

## 2.1 Climate Data and Site Assessment

Local climate stations with surface observations in the project area were identified and reviewed based on local topography and climate to determine their relevance to the project site. The surface observations including mean wind speeds, taken to be 10-minute mean wind speeds (per metadata provided by Australia Bureau of Meteorology when the data was obtained), and gust wind speeds, which are taken to be 0.2 second gust wind speeds for the period when the Dines Anemometers were used, and 3-second gusts for the rotating cup anemometers. A 10% upward factor was applied to the 3-second gust wind speeds to correct for the shorter averaging time of 0.2 seconds that the AS/NZS 1170.2:2021 wind speeds are representative of.

An inventory and review of the wind records available in the vicinity of the Causeway Pedestrian Bridges was conducted to identify meteorological stations with sufficiently long term and complete wind records that would be representative of the winds at the bridge site. Perth International Airport, approximately 10 km northeast of the bridge sites was the most suitable in terms of its exposure and location, with a 25-year period of record.

The wind statistics used to determine the design wind speeds at the Causeway Bridge sites were based on the surface wind measurements taken at the Perth International Airport. The meteorological station's data contains sufficiently long period of record (1997-2021) to perform a comprehensive statistical analysis for the determination of the regional wind climate in the area. Figure 2-1 shows the location of the meteorological station in relation to the two bridges.

The effect of the upwind terrain surrounding the anemometer and the bridge site were accounted for using the ESDU methodology described in Appendix A.1 on a direction-by-direction basis. This method was used to transpose the winds at the airport to the bridge site. By taking into consideration the upwind terrain profiles (on a direction-by-direction basis) at the airport anemometer, the measured wind records can be scaled up to gradient height, which is the height above that the roughness/terrain of the earth's surface no longer slows down/impacts the wind. This establishes a regional wind condition, independent of terrain. This gradient wind model can then be readily transposed to the bridge site. The gradient wind model can then be scaled down to the deck height of the bridge on a direction-by-direction basis, based on the terrain conditions at the bridge site. Figure 2-2 illustrates this method of how measured wind speeds are translated from the anemometer location to the bridge site at deck level.

A data quality review of the high wind speeds in the record was conducted to ensure that all high wind speeds included in the records were true wind events. Any erroneous data discovered were removed from the dataset to not skew the subsequent analyses.

## 2.2 Wind Climate Analysis

### 2.2.1 Regional Wind Climate

The extreme wind climate was assessed by applying two separate models to the historical data. First, an extreme value analysis model was used to assess the relationship between wind speed and return period by employing the exposure corrected historical wind records. This is described in Appendix A.2. Second, a directional Weibull model based was applied to the data, as described in Appendix A.3.

### 2.2.2 Comparison to AS/NZS 1170.2:2021

Wind speeds for design are provided in the Australian/New Zealand Standard (AS/NZS 1170.2:2021), Perth is in Region A1. The regional wind speeds ($V_R$) are provided (in Table 3.1 of AS/NZS 1170.2) for a range of mean recurrence intervals for serviceability through to ultimate load states. It has been established that the regional wind speeds in AS/NZS 1170.2-2021 are 0.2 second gust wind speeds not 3-second gust wind speeds. It is important to note that this is also reflected in the latest version of the Australasian Wind Engineering Society document "Wind Loading Handbook for Australia & New Zealand – Background to AS/NZS 1170.2 Wind Actions" (Ref.1), which was written by the code committee members of AS/NZS 1170.2-2011.

In standard open terrain conditions at 10 m, a 0.2-second gust wind speed is 10% higher than a 3-second gust wind speed, and 67% higher than a mean hourly wind speed.

According to the extreme value analysis conducted, the peak gust wind speed for the project location is 47.6 m/s corresponding to a mean recurrence interval of 2000 years. This is in good agreement with the 2000-year Region A regional wind speed in AS/NZS 1170.2:2021 which is $V_R$ = 48 m/s. Similarly, the 20- and 200-

year wind speeds from RWDI's wind climate model are 37.0 m/s and 42.3 m/s, respectively, which are also in good agreement the corresponding values from AS/NZS 1170.2:2021 (37 m/s and 43 m/s, respectively). Figure 2-3 shows the wind speeds in open terrain at an elevation of 10 m derived for the bridge site based on data from the airport, as well as the AS/NZS 1170.2:2021 wind speeds for various mean recurrence intervals.

### 2.2.3 Wind Speeds at the Bridge Sites

The ESDU analysis described in Appendix A.1 and Section 2.1 allow for the mean wind profile under strong winds to be determined at the bridge sites. This mean wind speed profile is applied in conjunction with the results of the extreme value analysis shown in Figure 2-3 to determine the relationship between 0.2-second gust wind speeds and return period at the bridge deck-level height of 8 m.

#### *2.2.3.1 McCallum Park Bridge*

The resulting deck-level wind speeds at the McCallum Park Bridge site have been presented in Figure 2-4 and Figure 2-5 at 8 m and summarized in Tables 2-1a and 2-1b. Due to a difference in exposure for winds coming from the two wind directions perpendicular to the bridge (50° and 230°), wind speeds and turbulence properties have been provided for both perpendicular wind directions. For a wind direction of 50° the 200- and 2000-year return period **mean hourly** wind speeds are 21.3 m/s and 24.0 m/s at 8 m, which are applicable for the design of the bridge during construction and the design of the completed bridge, respectively. For a wind direction of 230° the 200- and 2000-year return period mean hourly wind speeds are 21.6 m/s and 24.4 m/s at 8 m, which are applicable for the design of the bridge during construction and the design of the completed bridge, respectively.

To ensure the aerodynamic stability of the bridge, a 10-minute mean wind speed is used to account for the time required for aerodynamic instability to build-up. To reduce the probability of occurrence of an aerodynamic instability, the 1000-year return period is recommended for the bridge under construction and the 10,000-year return period is recommended for the completed bridge. The 1000- and 10,000-year return period 10-minute mean wind speeds at 8 m are 24.2 m/s and 27.0 m/s, respectively, for a wind direction of 50° and 24.4 m/s and 27.2 m/s, respectively, for a wind direction of 230°.

#### *2.2.3.2 Point Fraser Bridge*

The resulting deck-level wind speeds at the Point Fraser Bridge site have been presented in Figure 2-6 and Figure 2-7 at 8 m and summarized in Tables 2-1c and 2-1d. Due to a difference in exposure for winds coming from the two wind directions perpendicular to the bridge (50° and 230°), wind speeds and turbulence properties have been provided for both perpendicular wind directions. For a wind direction of 50° the 200- and 2000-year return period mean hourly wind speeds are 21.2 m/s and 23.8 m/s at 8 m, which are applicable for the design of the bridge during construction and the design of the completed bridge, respectively. For a wind direction of 230° the 200- and 2000-year return period mean hourly wind speeds are 23.0 m/s and 25.9 m/s at 8 m, which are applicable for the design of the bridge during construction and the design of the completed bridge, respectively.

The 1000- and 10,000-year return period 10-minute mean wind speeds at 8 m are 24.0 m/s and 26.8 m/s, respectively, for a wind direction of 50° and 25.9 m/s and 28.9 m/s, respectively, for a wind direction of 230°.

The directionality of the winds at the bridge site are presented in Figure 2-8. The strong winds in Perth come from the northwest and east wind directions. This is in contrast to the wind direction multiplication factors ($M_d$) for Region A1 in AS/NZS 1170.2:2021, which has the highest factors from southwest to northwest. Based on the directional model described in Appendix A.3, a wind directionality reduction factor for the bridge sites of **0.95** has been calculated. This 0.95 factor has been applied to the wind speeds for both strength design and stability as presented in Figures 2-4 to 2-7 and Tables 2-1a to 2-1d.

### 2.2.4 Turbulence Properties at the Bridge Site

The same ESDU methodology with a direction-by-direction assessment of upwind terrain was used to determine the wind speeds, turbulence intensities and length scales at deck height for the site. The turbulence intensities ($I_u$, $I_v$, $I_w$) and length scales (${}^xL_u$, ${}^xL_w$, ${}^yL_u$, ${}^yL_w$, and ${}^zL_w$), which are most important for the bridges' buffeting response or wind loading, to strong winds, are given at deck level in Table 2-2a for McCallum Park Bridge and Table 2-2b for Point Fraser Bridge.

# 3 CONCLUSIONS

This report provides an assessment of the wind conditions at the project site for the Causeway Pedestrian Bridges (Point Fraser Bridge and McCallum Park Footbridge) in Perth, Western Australia. If the bridge location, height, or alignment changes, RWDI should be notified to revisit any assumptions and the influence on any findings derived in this report.

# 4 REFERENCES

1. Holmes, J. D., Kwok, K. C. S., Ginger, J. D., & Walker, G. R. (2012). Wind Loading Handbook for Australia and New Zealand: Background to AS/NZS 170.2 Wind Actions.

# TABLES

**Table 2-1a: Recommended wind speeds at McCallum Park Bridge, 50°**

| Wind Speed Applicable for | Return Period (years) | Mean Wind Speed (m/s) at Deck Level 8 m and Averaging Time | | Corresponding 0.2-second Gust Speed (m/s) at 10 m Open Terrain |
|---|---|---|---|---|
| **Design during construction** | 200 | 21.3* | 1 h | 42.3 |
| **Design of completed bridge** | 2000 | 24.0* | 1 h | 47.6 |
| **Stability during construction** | 1,000 | 24.2* | 10 min | 46.0 |
| **Stability of completed bridge** | 10,000 | 27.0* | 10 min | 51.3 |

*Includes reduction due to extreme wind climate directionality

**Table 2-1b: Recommended wind speeds at McCallum Park Bridge, 230°**

| Wind Speed Applicable for | Return Period (years) | Mean Wind Speed (m/s) at Deck Level 8 m and Averaging Time | | Corresponding 0.2-second Gust Speed (m/s) at 10 m Open Terrain |
|---|---|---|---|---|
| **Design during construction** | 200 | 21.6* | 1 h | 42.3 |
| **Design of completed bridge** | 2000 | 24.4* | 1 h | 47.6 |
| **Stability during construction** | 1,000 | 24.4* | 10 min | 46.0 |
| **Stability of completed bridge** | 10,000 | 27.2* | 10 min | 51.3 |

*Includes reduction due to extreme wind climate directionality

**Table 2-1c: Recommended wind speeds at Point Fraser Bridge, 50°**

| Wind Speed Applicable for | Return Period (years) | Mean Wind Speed (m/s) at Deck Level 8 m and Averaging Time | | Corresponding 0.2-second Gust Speed (m/s) at 10 m Open Terrain |
|---|---|---|---|---|
| **Design during construction** | 200 | 21.2* | 1 h | 42.3 |
| **Design of completed bridge** | 2000 | 23.8* | 1 h | 47.6 |
| **Stability during construction** | 1,000 | 24.0* | 10 min | 46.0 |
| **Stability of completed bridge** | 10,000 | 26.8* | 10 min | 51.3 |

*Includes reduction due to extreme wind climate directionality

**Table 2-1d: Recommended wind speeds at Point Fraser Bridge, 230°**

| Wind Speed Applicable for | Return Period (years) | Mean Wind Speed (m/s) at Deck Level 8 m and Averaging Time | | Corresponding 0.2-second Gust Speed (m/s) at 10 m Open Terrain |
|---|---|---|---|---|
| **Design during construction** | 200 | 23.0* | 1 h | 42.3 |
| **Design of completed bridge** | 2000 | 25.9* | 1 h | 47.6 |
| **Stability during construction** | 1,000 | 25.9* | 10 min | 46.0 |
| **Stability of completed bridge** | 10,000 | 28.9* | 10 min | 51.3 |

*Includes reduction due to extreme wind climate directionality

**Table 2-2a: Turbulence properties at deck level of 8 m McCallum Park Bridge**

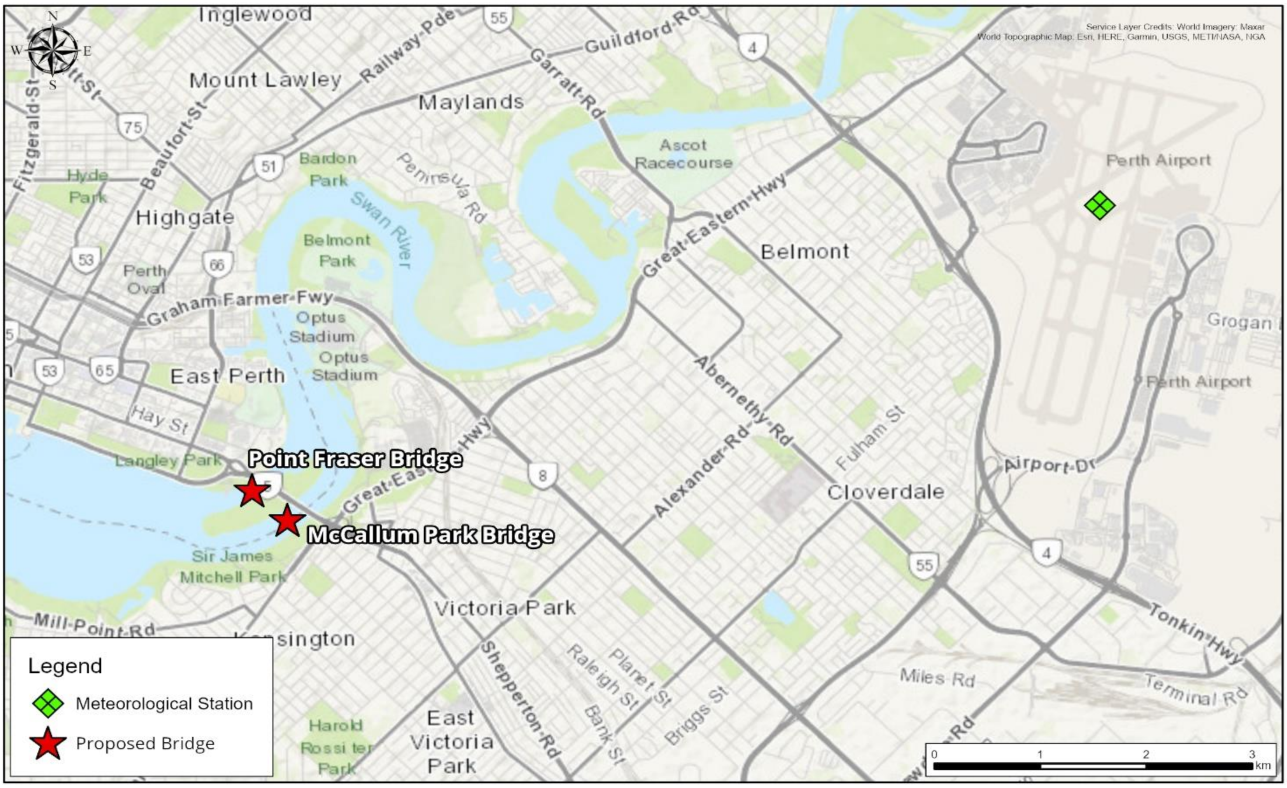
| Direction (°CW from N) | $Z_0$ (m) | $\alpha$ | $I_u$ (%) | $I_v$ (%) | $I_w$ (%) | $^xL_u$ (m) | $^xL_w$ (m) | $^yL_u$ (m) | $^yL_w$ (m) | $^zL_u$ (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **50** | 0.082 | 0.161 | 20.6 | 16.1 | 11.3 | 72 | 6 | 19 | 3 | 12 |
| **230** | 0.044 | 0.158 | 18.6 | 14.5 | 10.2 | 85 | 7 | 23 | 4 | 14 |

**Table 2-2b: Turbulence properties at deck level of 8 m Point Fraser Bridge**

| Direction (°CW from N) | $Z_0$ (m) | $\alpha$ | $I_u$ (%) | $I_v$ (%) | $I_w$ (%) | $^xL_u$ (m) | $^xL_w$ (m) | $^yL_u$ (m) | $^yL_w$ (m) | $^zL_u$ (m) |
|---|---|---|---|---|---|---|---|---|---|---|
| **50** | 0.086 | 0.163 | 20.7 | 16.1 | 11.4 | 71 | 6 | 19 | 3 | 11 |
| **230** | 0.026 | 0.144 | 17.3 | 13.5 | 9.5 | 97 | 8 | 26 | 4 | 16 |

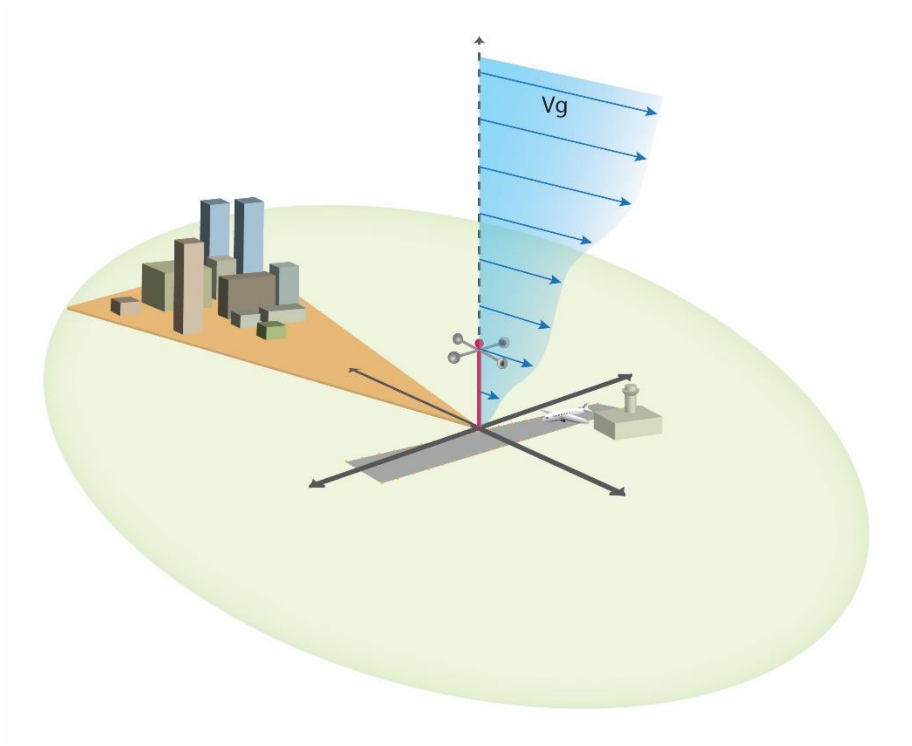
Notes:
1. $z_0$ - aerodynamic roughness
2. $\alpha$ - power law constant of wind profile
3. $I_{u,v,w}$ - longitudinal, horizontal-across-wind, and vertical turbulence intensities
4. $^{x,y,z}L_{u,v,w}$ - turbulence length scales

# FIGURES

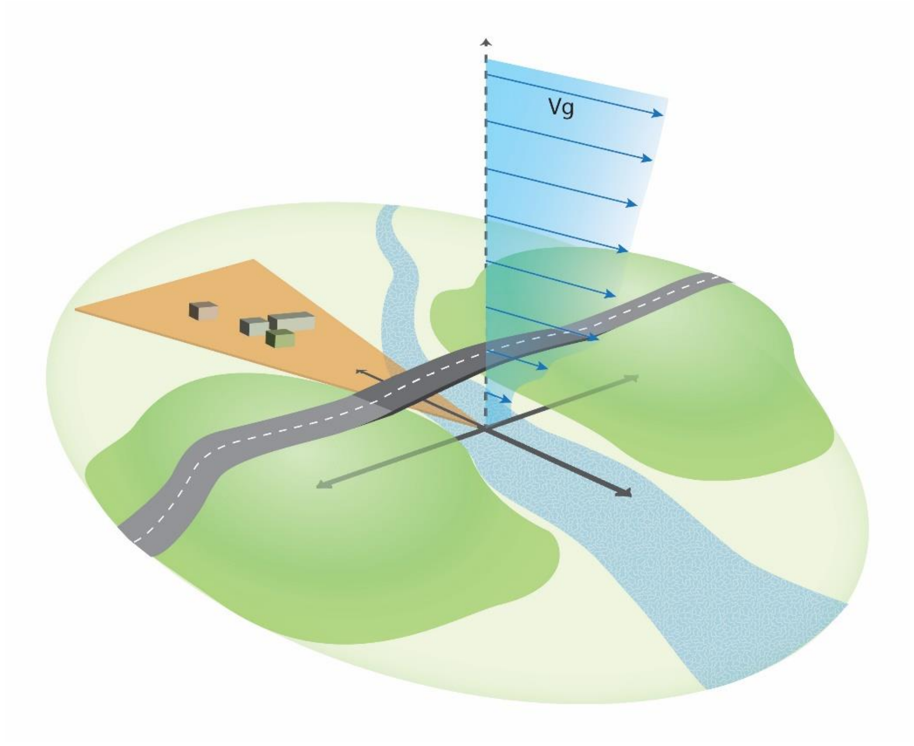




| **Location of the Causeway Pedestrian Bridges (McCallum Park Bridge and Point Fraser Bridge) and Climate Station** | Figure: 2-1 | |
|---|---|---|
| Causeway Pedestrian Bridges – Perth, Australia   Project #2100795 | Date: September 5, 2022 | |



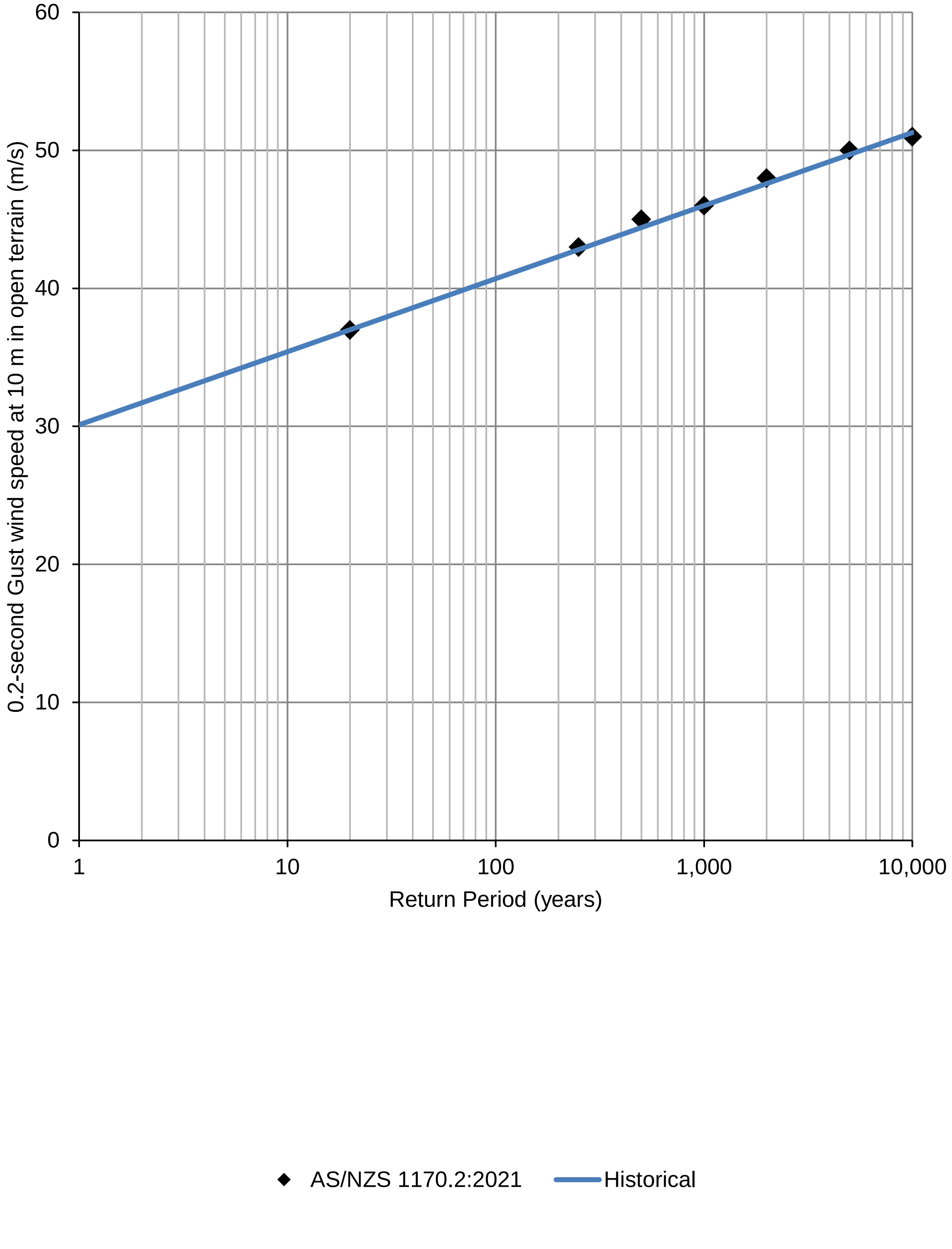

(a) Wind Profile at the Wind Measurement Location



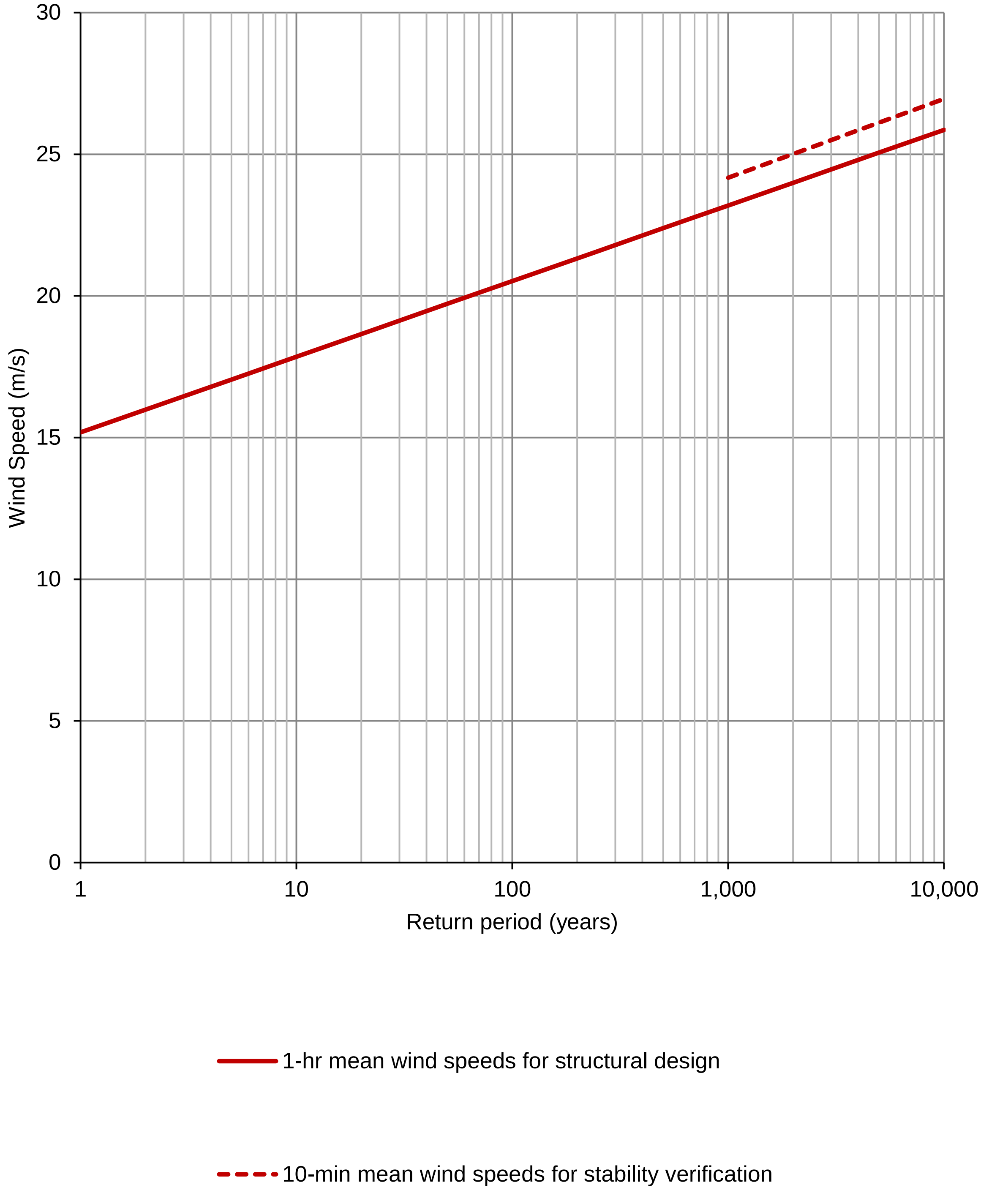

(b) Wind Profile at the Bridge Site

The upwind terrain at the airport or wind measurement site (a) influences the wind speed profile differently than at the bridge site (b), up to gradient height, which is the height beyond which the surface roughness has any influence on the wind speed or turbulence. The ESDU method described in Section 2.1 of this report calculates the wind speed profile based on the changes in the upwind terrain and their relative distance to the measurement location, up to gradient height. The gradient height wind speed can then be similarly scaled down to the bridge deck height based on the upwind terrain at the bridge site. Note that these figures are meant to be illustrative in nature and not representative of the specific project site.

| **Translating Wind Speeds from Measurement Location to Project Site** | Figure No. 2-2 | RWDI |
|---|---|---|
| Causeway Pedestrian Bridges – Perth, Australia — Project #2100795 | Date: September 5, 2022 | |




| **0.2-second Gust wind speed at 10 m in open terrain (m/s)** | | Figure: 2-3 |
|---|---|---|
| Causeway Pedestrian Bridges – Perth, Australia | Project #2100795 | Date: September 5, 2022 |




**Mean Wind Speed for Various Return Periods McCallum Park Bridge 50°**

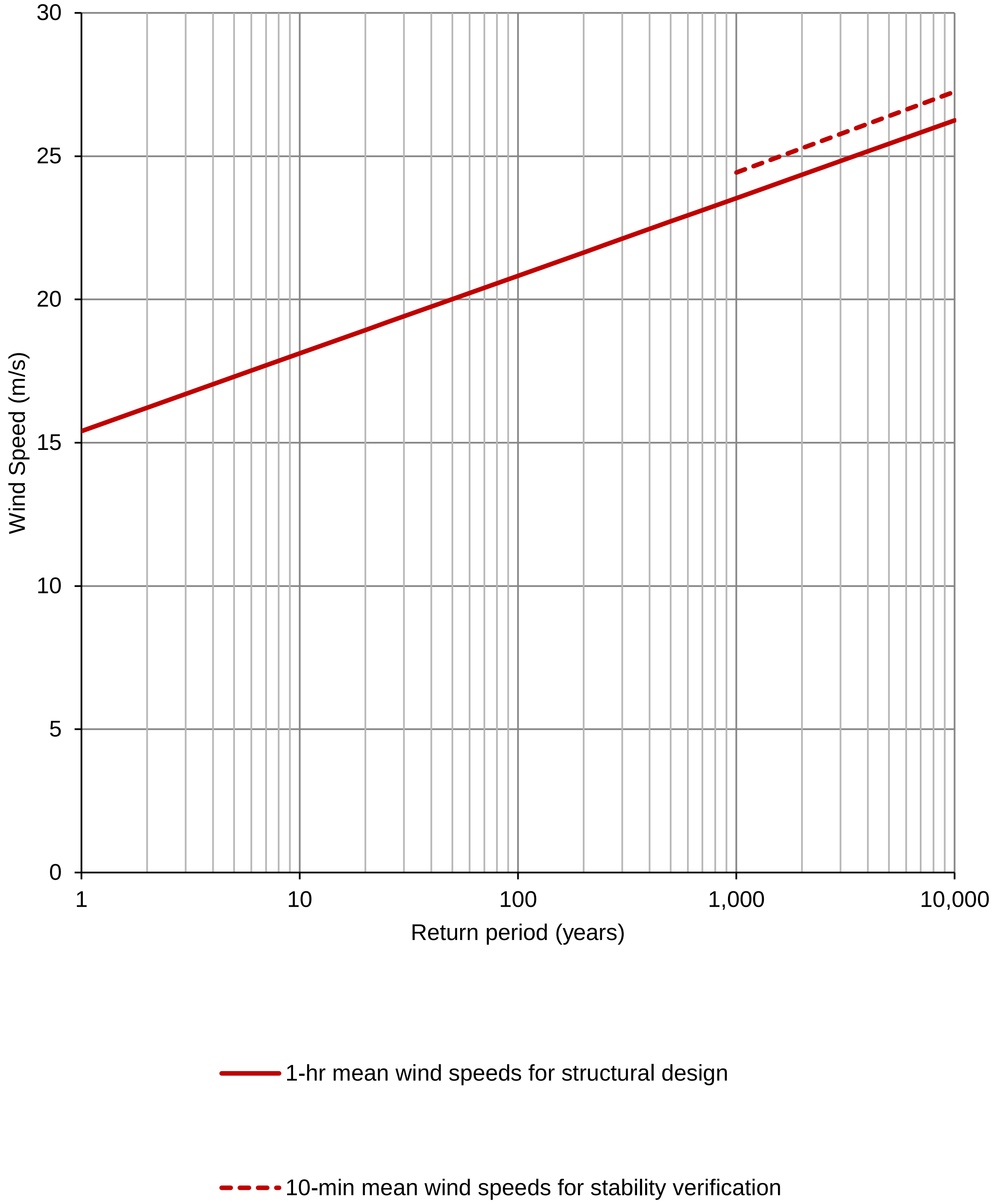
Wind speeds at elevation 8 m above grade

Figure: 2-4

Causeway Pedestrian Bridges – Perth, Australia

Project #2100795

Date: September 5, 2022




**Mean Wind Speed for Various Return Periods McCallum Park Bridge 230°**

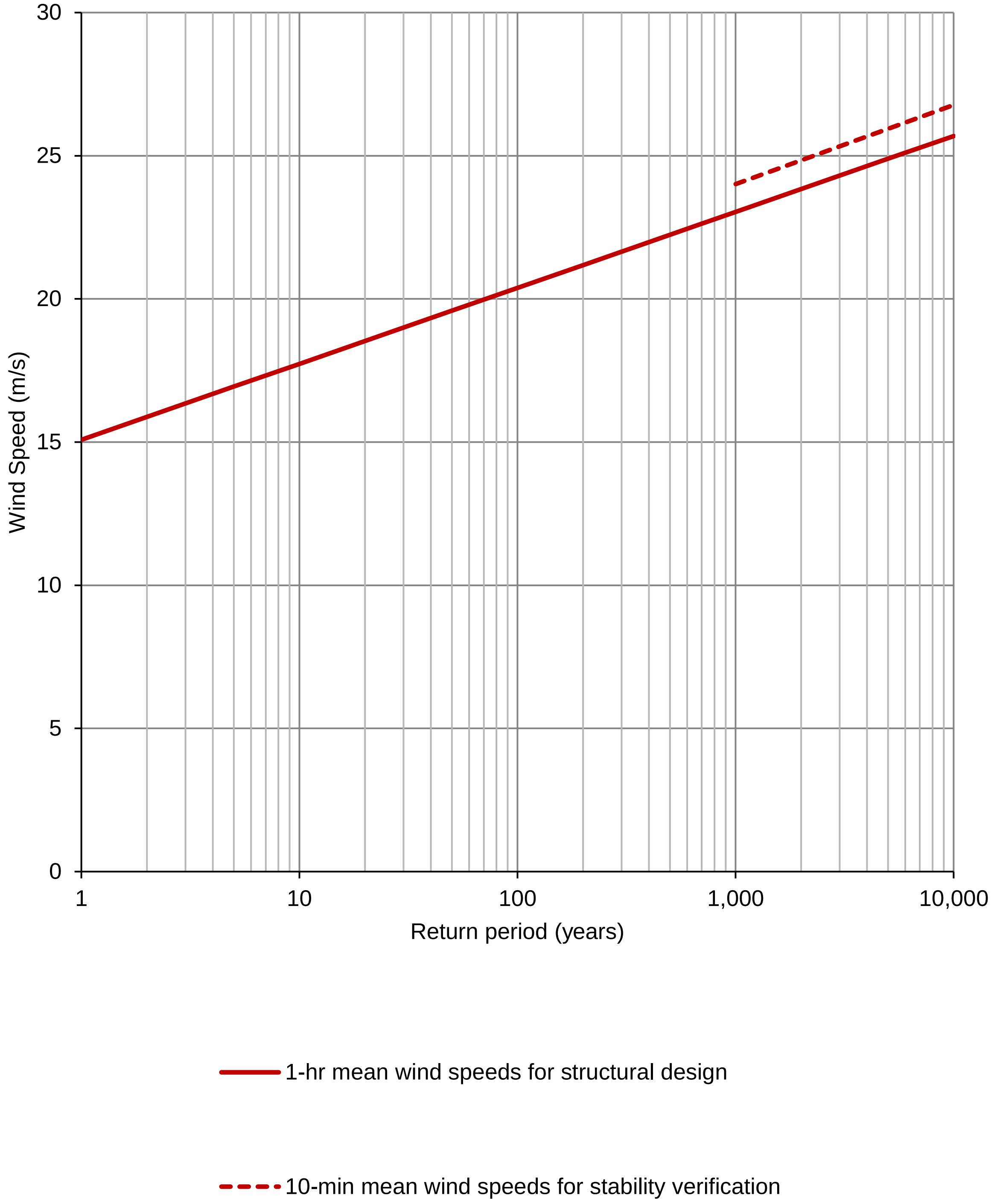
Wind speeds at elevation 8 m above grade

Figure: 2-5

Causeway Pedestrian Bridges – Perth, Australia

Project #2100795

Date: September 5, 2022




**Mean Wind Speed for Various Return Periods Point Fraser Bridge 50°**

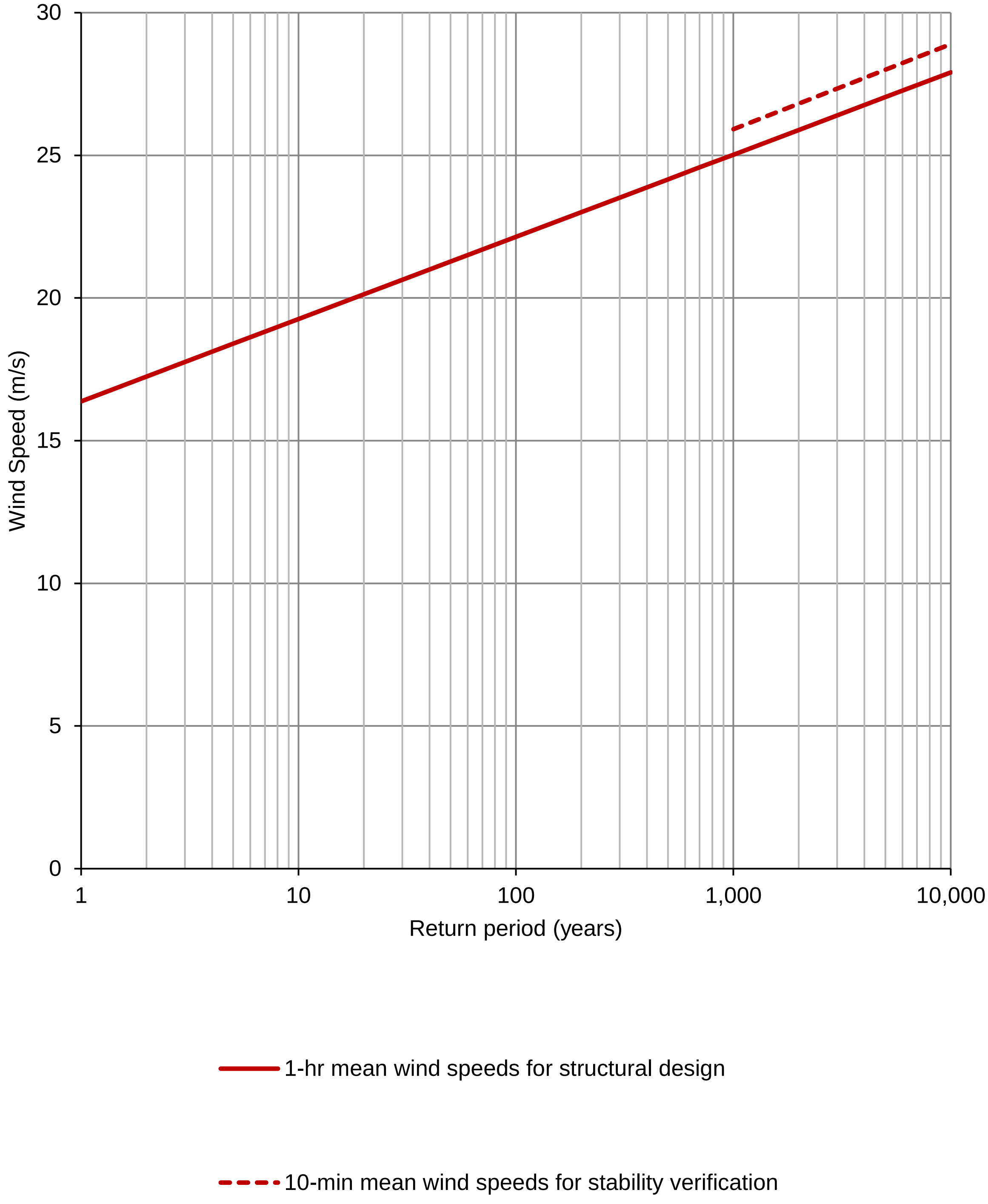
Wind speeds at elevation 8 m above grade

Figure: 2-6

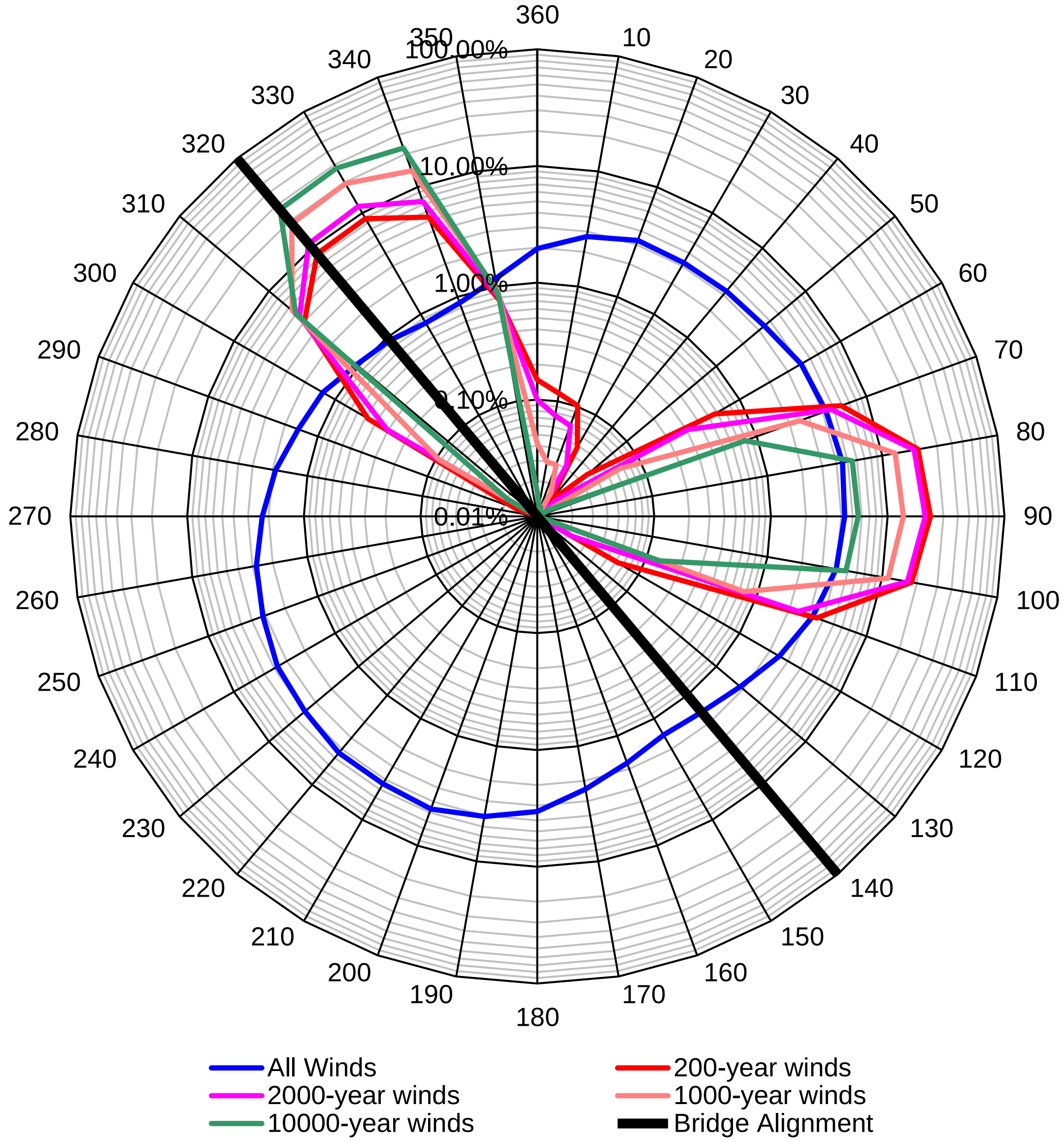
Causeway Pedestrian Bridges – Perth, Australia

Project #2100795

Date: September 5, 2022




| | | |
|---|---|---|
| **Mean Wind Speed for Various Return Periods Point Fraser Bridge 230°**<br>Wind speeds at elevation 8 m above grade | Figure: 2-7 | |
| Causeway Pedestrian Bridges – Perth, Australia   Project #2100795 | Date: September 5, 2022 | |




| **Directional Distribution of Hourly Mean Winds at the Project Site** | Figure: 2-8 |
|---|---|
| Causeway Pedestrian Bridges – Perth, Australia Project #2100795 | Date: September 5, 2022 |

# APPENDIX A

# APPENDIX A.1: TERRAIN CORRECTION WITH ESDU

Special attention is given to the analysis of the hourly records to account for the effects of the terrain surrounding an anemometer. Typically, anemometers are installed in an open terrain exposure that is used as a reference condition by building codes. However, this is rarely the case in real world applications. This means the true exposure of the anemometer is not that of the standard open terrain conditions. It is important to take this impact into account so as to avoid underestimating or overestimating design wind speeds.

Prior to conducting any analysis using the surface observations, the effect of upwind terrain roughness and land cover characteristics on the wind speeds at the anemometer station is assessed for each wind direction, and used to adjust wind speeds to a standard open terrain profile.

ESDU[1],[2] describes a method based on the work of Deaves and Harris[3] for evaluating changes in the mean velocity profile following a change in ground roughness. This is particularly useful when analyzing meteorological records from an anemometer surrounded by varying terrain roughness for different wind directions.

This method is used to determine anemometer exposure. Maps, photographs and satellite imagery of the location are used to assess the ground roughness changes for each wind direction. The wind speeds for each wind direction were then adjusted based on the exposure of the anemometer to produce wind speeds that are equivalent to standard open terrain.

---

[1] ESDU (1982) *Strong Winds in the Atmospheric Boundary Layer. Part 1: Mean Hourly Speeds*, Item 82026, Issued September 1982 with Amendments A and B April 1993. Engineering Sciences Data Unit, ESDU International, 27 Corsham Street, London N16UA.

[2] ESDU (1983) *Strong Winds in the Atmospheric Boundary Layer. Part 2: Discrete Gust Speeds*, Item 83045, Issued November 1983 with Amendments to 1993. Engineering Sciences Data Unit, ESDU International, 27 Corsham Street, London N16UA.

[3] Deaves, D.M. and Harris, R.I. (1978) *A Mathematical Model of the Structure of Strong Winds*, Construction Industry Research and Information Association (U.K.), Report #76.

# APPENDIX A.2: PREDICTION OF EXTREME WINDSPEEDS AND THE METHOD OF INDEPENDENTSTORMS

The first step in conducting an extreme value analysis for predicting wind speed frequency is producing a set of independent maxima which will ultimately be fitted to an extreme value distribution. Traditionally, this would be done using readily available data sets of annual maxima. Since the resolution of this data is relatively low, the likelihood of neighboring years having maxima that are related to the same wind event is quite low, and so they can generally be assumed to be independent. However, using annual maxima for this purpose means that many high wind events that occur will not be considered in the assessment of risk if they are not the highest event in a given year. To illustrate this, consider the 2 years of time series of wind data in Figure 1. There are actually 3 independent wind events of higher speed in the year 1964 than in the year 1965. Considering only the annual maxima would result in 2 of those high wind events being ignored, and could result in an under-prediction of the true risk.

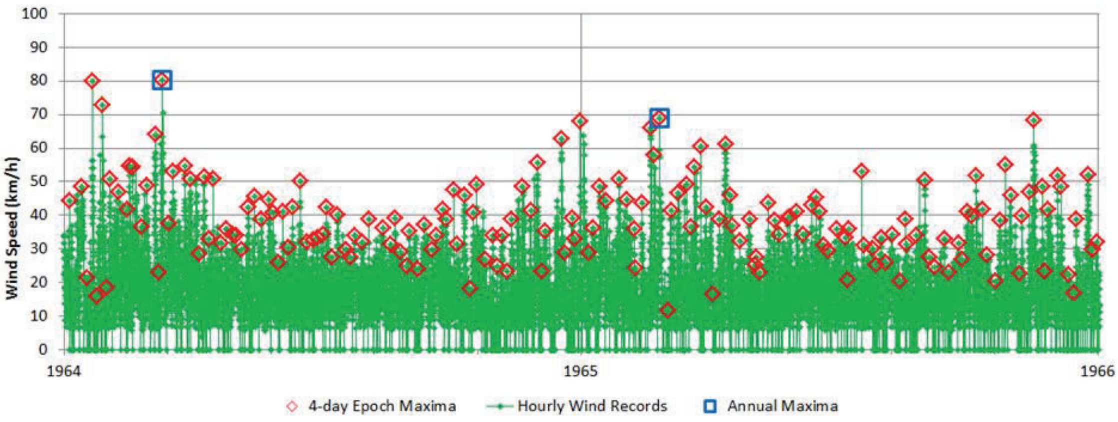



*Figure 1: 4-day Epoch Maxima in Comparison to Annual Maxima*

As you reduce the size of the epoch considered for selecting maxima, you also increase the probability of selecting maxima from neighboring epochs that are actually part of the same wind event, so it becomes increasingly important to verify independence. The Method of Independent Storms (MIS) is an extreme value technique described by Cook[1], and then subsequently updated by Harris[2]. As the name suggests, MIS ensures that the maxima included for extreme value fitting are selected from independent events.

[1] Cook, N.J. (1982) *Towards better estimation of extreme winds*, Journal of Wind Engineering and Industrial Aerodynamics 9, pp.295-323.

[2] Harris, R.I. (1999) *Improvements to the method of independent storms*, Journal of Wind Engineering and Industrial Aerodynamics 80, pp.1-30.

RWDI's implementation of MIS separates the historical dataset into 4-day epochs. The selection of a 4-day epoch is based on the wind power spectrum, which tends to peak at approximately 4 days due to the normal duration of a synoptic pressure system in an extra-tropical climate. Within the 4-day epoch, a local minimum is determined. This forms a series of minima throughout the historical dataset. A second set of epochs is defined by the minima, between which a local maximum is selected. This process is illustrated in Figure 2.

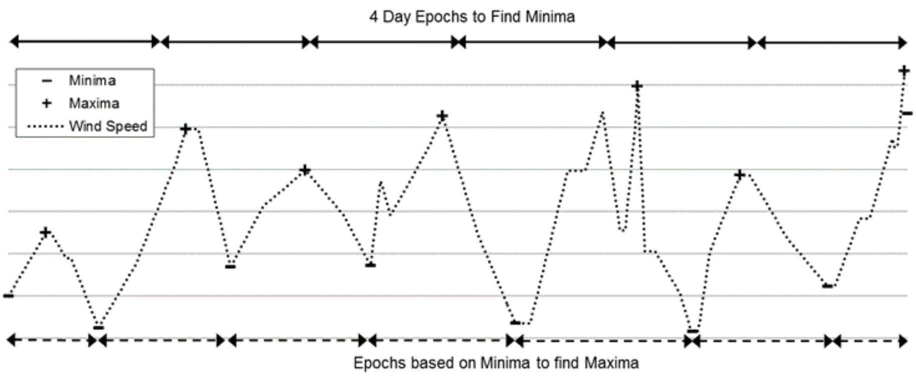



*Figure 2: Maxima and Minima-Finding Routine*

This process is applied to the entire dataset and the maxima are ranked according to wind speed. Finally, each wind speed is assigned a probability based on rank according to the Gringorten Probability Method[3]. These speeds are fit to a Fisher-Tippet Type I distribution, which is given by:

$$P(\hat{U}) = e^{-e^{-y}} \qquad (1)$$

where $P(\hat{U})$ is the probability that the annual peak velocity will not exceed the value, and $\hat{U}$ is the peak velocity.

The parameter y is defined as:

$$y = a(\hat{U} - b) \qquad (2)$$

in which 1/*a* is dispersion and *b* is the mode.

[3] Gringorten, I.I. (1963) *A plotting rule for extreme probability paper*, Journal of Geophysical Research 68(3), pp.813-814.

# APPENDIX A.3: DIRECTIONAL DISTRIBUTION OF WINDS AND THE WEIBULL DISTRIBUTION

A commonly used mathematical expression that models wind statistics fairly well is the Weibull expression, which can be stated as:

$$P_\theta(>U) = A_\theta \times e^{-\left(\frac{U}{C_\theta}\right)^{K_\theta}} \qquad (1)$$

where is the probability that the mean wind speed will exceed the value U when the wind direction is within the azimuthal sector θ. The $A_\theta$ factor is the fraction of the time that the wind blows from the selected sector, and $C_\theta$ and $K_\theta$ are the velocity and shape parameters required for each of the direction sectors. A variant on this Weibull expression that fits the higher wind speeds separately, and ultimately provides a better fit to the higher wind speeds, was used and its expression is:

$$P_\theta(>U) = \begin{cases} if\ U_z < U_{th_\theta},\ \ A_\theta \times e^{-\left(\frac{U_z}{C_{L\theta}}\right)^{K_{L\theta}}} \\ \\ if\ U_z \geq U_{th_\theta},\ \ A_\theta \times e^{-\left(\frac{U_z}{C_{U\theta}}\right)^{K_{U\theta}}} \end{cases} \qquad (2)$$

where $C_{L\theta}$ and $K_{L\theta}$ are the Weibull parameters for wind speeds below the threshold velocity $U_{th\theta}$, and $C_{U\theta}$ and $K_{U\theta}$ are the Weibull parameters for wind speeds greater than or equal to the threshold velocity for wind direction θ. The Weibull expression is fitted to the mean hourly using wind direction intervals of 10 degrees.

To compute the functional relationship between wind speed and return period the Upcrossing Method described by Lepage and Irwin (1985) and Irwin (1988) is used. Using this method, it can be shown that the frequency F of an event where the wind velocity U will be exceeded is given by:

$$F(>U) = \frac{1}{2}\sum_\theta \overline{|\dot{U}|} \times \frac{dP_\theta(U)}{dU} \qquad (3)$$

from which the return period *R* of wind velocity *U* may be determined as:

$$R = \frac{1}{n \cdot F(> U)} \qquad (4)$$

where $n$ is the number of hours per year and $\overline{|\dot{U}|}$ is the mean absolute rate of change of the hourly wind velocities.

From the probability distributions given by the equations above, the overall probability of wind speed is obtained by summing over all wind directions.