FINAL REPORT

WIND CLIMATE ANALYSIS
BRENT SPENCE BRIDGE
CINCINNATI, OH

CONSULTING ENGINEERS & SCIENTISTS

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1. INTRODUCTION

RWDI was retained by Parsons Brinckerhoff (PB) to conduct wind engineering studies for the proposed new renovation of the Brent Spence Bridge (BSB), which is located in Cincinnati, Ohio. The new bridge is on the west side of the existing BSB. Three bridge options are currently being developed by the designers Parsons Brinckerhoff. The following reports RWDI's wind engineering studies performed for the new bridge.

These include:

- **Local Wind Climatology Analysis:** The objective of this analysis was to determine the design wind speeds for wind loading.

2. WIND CLIMATE ANALYSIS

2.1 INTRODUCTION

This section of the report presents the analysis of the wind climate and wind turbulence properties undertaken for the bridge site in Cincinnati, Ohio. The results presented in this section will be used in the subsequent analyses to determine the aerodynamic stability of the bridge. Figure 2-1 provides a site plan showing the location of the bridge and local meteorological stations used in this analysis. Photographs of the site taken during our visit on July 7, 2010 are shown in Figures 2-2 and 2-3.

2.2 WIND CLIMATE AND SITE ANALYSIS

2.2.1 Source of Data

The wind statistics used to determine the design wind speeds and directionality at the bridge site were based primarily on the surface wind measurements taken between 1948 and 2008 at the Cincinnati-Northern-Kentucky International Airport, located about 8 miles west-southwest from the bridge site. Wind data for 1973 to 2009 from the Cincinnati Municipal Airport, located 5.6 miles east of the site were also used to provide additional insight into winds in the area. However, since this airport is located in a valley and sheltered for almost all wind directions, it was considered more prudent not to use this data for the final interpretation and the design wind speeds.

2.2.2 Local Terrain

The terrain surrounding the airport anemometer and the bridge site were reviewed based on satellite images, topological maps and site photographs. Adjustments were made, where necessary, for the terrain roughness upwind of the anemometer and for its height above the ground. On July 7, 2010, a RWDI engineer went to the bridge site to take photographs and to confirm the terrain information used in the analysis (see Figures 2-2 and 2-3).

2.2.3 Analysis

The design wind speeds and directionality for the bridge site were determined using the following steps:

i. Extreme value analyses using a Fisher-Tippet Type I distribution were conducted based on the wind records collected at the Cincinnati-Northern-Kentucky International Airport.

ii. The joint probability of wind speed and direction for the site was determined based on the available meteorological data. The analyzed wind data were then expressed in the form of a mathematical model for the airport.

iii. The mathematical model developed in (ii) was used to evaluate wind speed as a function of return period and also to evaluate the component of the wind velocity normal to the bridge span as a function of return period. The procedure called "Upcrossing Analysis" was used in this step.

All results contained in this report are discussed as mean-hourly (i.e., 1-hour mean) speeds, which are applicable for structural design, or as 10-minute mean speeds. In this study, 10-minute mean speeds are given since this is the typical time for an aerodynamic instability to develop on a bridge sensitive to wind. According to the wind map of the ASCE 7-05 Standard, a 90 mph basic design wind speed for the Cincinnati area is recommended, this being a 3-sec gust speed in open terrain at 33ft height. To relate the mean-hourly wind speed to the 3-second gust or 10-minute mean, the relationship shown in Figure C6-4 of the ASCE 7-05 was assumed. According to this curve, 1-hour mean wind speeds can be converted to 3-second gust speeds, and to 10-minute mean speeds multiplying by the factors 1.524 and 1.067, respectively. Using the factor 1.524 to convert from a 3-second gust speed to a mean hourly wind speed, the basic design wind speed for Cincinnati becomes 59.2 mph. Adjustments for other terrain conditions were made using ESDU methodology[1].

2.2.4 Extreme Value Analysis to Determine Design Winds

Meteorological data from the Northern-Kentucky International Airport were used to calculate extreme wind speed return periods. The maximum mean-hourly wind speeds occurring each month were extracted for the period of record, and the velocities fitted to a Fisher-Tippet Type I distribution. Various fitting methods were used which included fitting velocities as well as velocity pressures, using both a least-squares fitting method and the method of moments. A comparison of the various fitting methods was used to evaluate the best fit to the data. The resulting distributions were then employed to predict wind speeds for a range of return periods (i.e., from 1 to 10,000 years).

1 Engineering Sciences Data Unit, Characteristics of the Atmospheric Turbulence Data Near the Ground: Part III, Variations in Space and Time for Strong Winds, ESDU 86010, London ,UK, 1986.

2.2.5 Joint Probability of Wind Speeds and Directions

A mathematical model of the joint probability of wind speed and direction was fitted to the meteorological wind data assuming a Weibull type distribution. This distribution expresses the probability of the wind speed at a given elevation exceeding a value U as

$$P_\theta(U) = A_\theta \exp\left[-\left(\frac{U}{C_\theta}\right)^{K_\theta}\right], \qquad (2\text{-}1)$$

where P_θ is the probability of exceeding the wind speed U in the angle sector θ;

θ is the central angle of an angle sector, measured clockwise from true North; and

A_θ, C_θ, K_θ are coefficients selected to give best fit to the data.

Note that A_θ is the fraction of time the wind blows from within the angle sector θ. The size of angle sectors used in this analysis was 10 degrees. To provide additional flexibility in curve fitting for normal winds, two Weibull curves were fitted, one to lower velocities and one to higher velocities, with blending expressions being used to provide a smooth transition.

The probability distributions given by Equation (2-1) may be used to obtain the overall probability of wind speed by summing over all wind directions.

$$P(U) = P_N(U) = \sum_\theta \left[P_{\theta N}(U)\right], \qquad (2\text{-}2)$$

where the subscript N refers to normal winds.

At the gradient height the wind speeds are well above the earth's surface roughness effects. The height used for determining gradient speed was 2000 ft. Since the anemometer is near ground level at the bottom of the planetary boundary layer, it is affected by ground roughness. These ground roughness effects were assessed using the methods given in ESDU[2] combined with information on the local terrain roughness gathered from topographic maps and other site information. Factors were developed to convert the anemometer records to wind speeds at gradient height and then to the bridge site.

2 ESDU International, Computer program for wind speeds and turbulence properties: flat or hilly sites in terrain with roughness changes, ESDU 01008, 2001.

2.2.6 Upcrossing Method to Determine Directionality Effects on Design Winds

By adapting random noise theory to meteorological data (Rice[3]), it can be shown that the return period, R, in years of a given gradient wind speed, U_G, is related to $P(U_G)$ by

$$R = -\left[\frac{\overline{|\dot{U}_N|}}{2} \frac{dP_N(U_G)}{dU_N} (T_A) \right]^{-1}, \tag{2-3}$$

where $\overline{|\dot{U}_N|}$ is the average of the absolute rate of change of the hourly values of U for normal winds with time; T_A is the total number of hours in a year, i.e., $T_A \approx 8766$.

Equation (2-3), together with an empirical relationship for $\overline{|\dot{U}_N|}$, can be used to determine the return periods for a series of selected wind speeds. The wind speed corresponding to a required return period (e.g., 10, 100, 1000 years etc.) can then be determined by interpolation. This method, which here uses the Weibull distribution for P_N, is called the Upcrossing Method and is one way of obtaining the variation of wind speed with return period. The other way is direct extreme value analysis as in Section 2.2.4. The direct method uses fewer assumptions. Therefore, the Weibull model was scaled to match the direct extreme value results exactly at each return period of interest. This approach allows directionality effects to be systematically accounted for by a model that is also consistent with extreme value analysis.

Since there is evidence[4] that for flutter instability the important component of wind velocity is that normal to the span, it is of interest to evaluate this normal component as a function of its return period. It can be shown[5,6] that if U_B denotes the wind velocity on the boundary of instability (in this case, the flutter velocity as defined for wind normal to the span, divided by the cosine of the actual angle between the wind direction and the normal to the span), then the return period *R* is given by

$$R = -\left[\sum_{\theta} \left(\frac{\overline{|\dot{U}_{NB}|}}{2} \frac{dP_{\theta N}}{dU_{NB}} \sqrt{1 + \left(\frac{\overline{|\dot{\theta}_{NB}|}}{\overline{|\dot{U}_{NB}|}} \frac{dU_{NB}}{d\theta_N} \right)^2} (T_A) \right) \right]^{-1}, \tag{2-4}$$

3 Rice, S.O., Mathematical Analysis of Random Noise, *The Bell System Technical Journal*, Vol. 23, 1944.

4 Irwin, P.A. and Schuyler, G.D., Experiments on a Full Aeroelastic Model of Lions' Gate Bridge in Smooth and Turbulent Flow. National Research Council of Canada, *NAE Report LTR-LA-20*6, 1977.

5 Lepage, M.F., and Irwin, P.A., A Technique for Combining Historic Wind Data with Wind Loads, *Proc. 5th U.S. National Conference on Wind Engineering*, Lubbock, Texas, 1985.

6 Irwin, P.A., Prediction and Control of the Wind Response of Long Span Bridges with Plate Girder Decks, *Proc. Structures Congress '87/ST Div/ASCE*, Orlando, Florida, August 17-20, 1987.

where $\left|\overline{\dot{U}_{NB}}\right|$ and $\left|\overline{\dot{\theta}_{NB}}\right|$ are the averages of the absolute rates of changes of wind speed and wind direction for normal winds.

2.3 RESULTS

2.3.1 Mean-Hourly Speeds at 33 ft Height in Open Terrain

Our analysis of the Cincinnati-Northern-Kentucky International Airport wind data indicated a 50-year return period speed of 52 mph, mean hourly in comparison with the recommended ASCE 7-05 wind speed of 59.2 mph, which implies some conservatism in the code speed for this location. Considering the complexity of the local terrain however, the obtained results were scaled to comply with code recommended speed. It should be noted that this wind study recommends wind speeds applicable for design and stability following the currently accepted practice for bridge design in North America.

Figure 2-4 shows various wind speeds at 33 ft elevation for an open terrain as a function of return period. This figure present the following information:

- mean hourly speeds at 33 ft elevation for return periods from 1 to 10,000 years derived from the available meteorological data from the Cincinnati-Northern-Kentucky International Airport;

- mean hourly speeds at 33 ft elevation for open terrain derived from the ASCE 7-05 recommended 3-sec gust speed for the Cincinnati area; and

- the 10-min mean speed for 1,000 and 10,000-year return periods.

Mean-hourly speeds are to be used for derivation of design loads whereas 10-min speeds are to be applied for stability assessments.

2.3.2 Wind Directionality Effects

Figure 2-5 shows probability of exceeding various mean-hourly wind speeds at a 105' deck height as a function of wind direction. The curves show the probability of exceeding wind speeds with 10, 100, 1000 and 10,000 year return periods as a function of wind direction. Also the probability of all winds, based on entire wind record data set is shown. The proposed bridge main span axis is oriented at approximately 2 degrees from the north-south alignment. Therefore, winds normal to the span would blow from approximately east and west. Figure 2-5 shows that the most probable directions for strong winds (e.g., once in 100 years) would likely be rotated slightly toward north and south of the main west direction (i.e., from about 250 and 290 degrees). Since the loading of individual structural components varies differently with wind direction, it is difficult to develop a generally applicable directionality reduction factor for all structural components. Some structural elements reach peak loading in quartering winds. This, combined with the above-mentioned alignment of strong winds, indicated to us that for this stage no directionality reduction should be applied to the wind loads for design winds. There is evidence (Irwin and Schuyler[4]) that flutter instability is essentially a function of the wind velocity component normal to the span. However, based on the directionality of the meteorological models near the bridge site and the orientation of the span, a significant directionality reduction is not expected. Therefore, no directionality reduction factors have been applied to the wind speeds for stability assessment or design wind loading.

From the information available for the bridge site (satellite images, topological maps and site photographs), it appears that large hills located on the south side of the Ohio River could shelter and deviate the wind flow. Bearing in mind the strong winds coming from southwest (as presented in Figure 2-5), an investigation was undertaken to determine if the hills to the southwest were significant enough to be diverting the southwest winds at the bridge site.

2.3.3 Wind Directionality Effects – Investigation of the southwest hills impact

RWDI used software called MS-Micro by Zephyr North[7] for estimating the directional deviation at the bridge site. This program uses a digital terrain information to estimate localized effects of complex terrain on wind. A numerical simulation was carried out on a domain of 9.3 miles by 9.3 miles at a grid resolution of approximately 394 ft. The simulation entailed 36 wind directions in 10 degree increments. Directional deviations were extracted at the bridge location at deck height for all 36 wind directions. The results showed the winds from the south deviating slightly to the east (counter-clockwise), and winds from the southwest and west deviate slightly more to the north (clockwise), which indicates that the winds are being diverted around the hills to the southwest of the bridge. The maximum directional deviation over all wind directions was however less than 4 degrees. Since the directional resolution of the historical data is 10 degrees, i.e. with precision lower than the expected flow deviations, no adjustment to the historical wind direction data was applied.

2.3.4 Terrain at the Bridge Site

The terrain surrounding the existing bridge is generally a combination of open water, urban and suburban areas and wooded countryside. To assess the terrain effects, the ESDU method was used. The wooded countryside and suburban areas were taken as having roughness lengths in the range of z_0 = 0.3 ft to 2.3 ft. The roughness lengths of the water fetches were classified following the ESDU recommendations being in the range of 0.003 ft to 0.008 ft. In terms of the traditional power law, in which mean velocity varies with height to the power of an exponent α, where this value ranges from 0.14 to 0.19.

2.3.5 Wind Speeds at Deck Height

The ratio of the mean velocity at a deck height of 105 ft to the mean velocity in standard open terrain at 33 ft (from Section 2.3.1) was found to be 1.08. The 100-year mean-hourly velocity at a height 105 ft was predicted to be 66.3 mph. Figure 2-6 also shows the 10-minute mean wind speeds at the deck height as a function of return period relevant for this study.

[7] http://zephyrnorth.com/index.html

2.3.5.1 Structural Design Wind Speed

For structural design of major bridges, a return period of 100 years is typically used. As described in the previous section, the 100-year mean-hourly speed was estimated to be 66.3 mph at a height of 105 ft (Table 2-1). For the construction phase, return period 20 years is typically recommended giving mean-hourly speed of 60.4 mph.

2.3.5.2 Design Wind Speed for Aerodynamic Stability

For flutter instability of the completed bridge, a very long return period needs to be considered because, if flutter occurs, there is a very high probability of structural failure. The recommended return period is 10,000 years. Since directionality reduction effects are not available (see section 2.3.2), the mean-hourly velocity for 10,000-year return period was determined as 81 mph. As previously discussed, flutter oscillations can build up over shorter periods than 1 hour; therefore, normally 10-minute mean value is applied. Using the ratio of 1.067 to scale mean hourly speeds to 10-minute mean speeds, the design speed for flutter is thus calculated to be 1.067 × 80.9 mph = 86.3 mph. For construction, a shorter return period is justifiable due to the shorter length of exposure during the construction period, and 1,000 years is recommended. The 1,000-year design flutter speed, arrived at by a similar approach, is 1.067 × 74.0 m/s = 79 mph.

2.3.6 Turbulence Properties at the Bridge Site

The same ESDU methodology used in determining the wind speeds at a height of 105 ft was also applied for the estimation of turbulence intensities and length scales at the site. The turbulence intensities (I_u, I_w, I_v and length scales (${}^xL_u$, ${}^xL_w$, ${}^yL_u$, ${}^yL_w$, and ${}^zL_w$), which are most important for the buffeting response of long-span bridges to strong winds, are given in Table 2-2.

2.4 WIND CLIMATE ANALYSIS: SUMMARY

The design wind speeds resulting from the wind climate and site analysis for the Brent Spence Bridge are summarized in Table 2.1. The resulting turbulence properties are shown in Table 2-2. The mean-hourly speeds are recommended for bridge design, and the 10-minute mean speeds are suggested for stability evaluations both during construction and for the completed bridge. The long-term wind records from the Cincinnati-Northern-Kentucky International Airport were the primary source of data used, although the data for Cincinnati Municipal Airport were also considered. Open water and the wooded/suburban/urban terrain around Cincinnati affect the exposure of the bridge site. These terrain effects have been accounted for arriving at the recommended speed values given in Table 2-1 and the turbulence properties in Table 2.2. The impact of the southwest hills was also investigated where the numerical assessment demonstrated that the wind deviation resulting from the interference of the proximity hills with the wind flow is negligible.

TABLES

Table 2-1: Recommended wind speeds at the site

Wind Speed Applicable for	Return Period (years)	Mean Wind Speed (mph) at Deck Level 105 ft and Averaging Time		Corresponding Mean Hourly Wind Speed (mph) at 33 ft Open Terrain
Design during construction	20	60.4	1 h	56.1
Design of completed bridge	100	66.3	1 h	61.5
Stability during construction	1,000	79	10 min	68.6
Stability of completed bridge	10,000	86.3	10 min	75.0

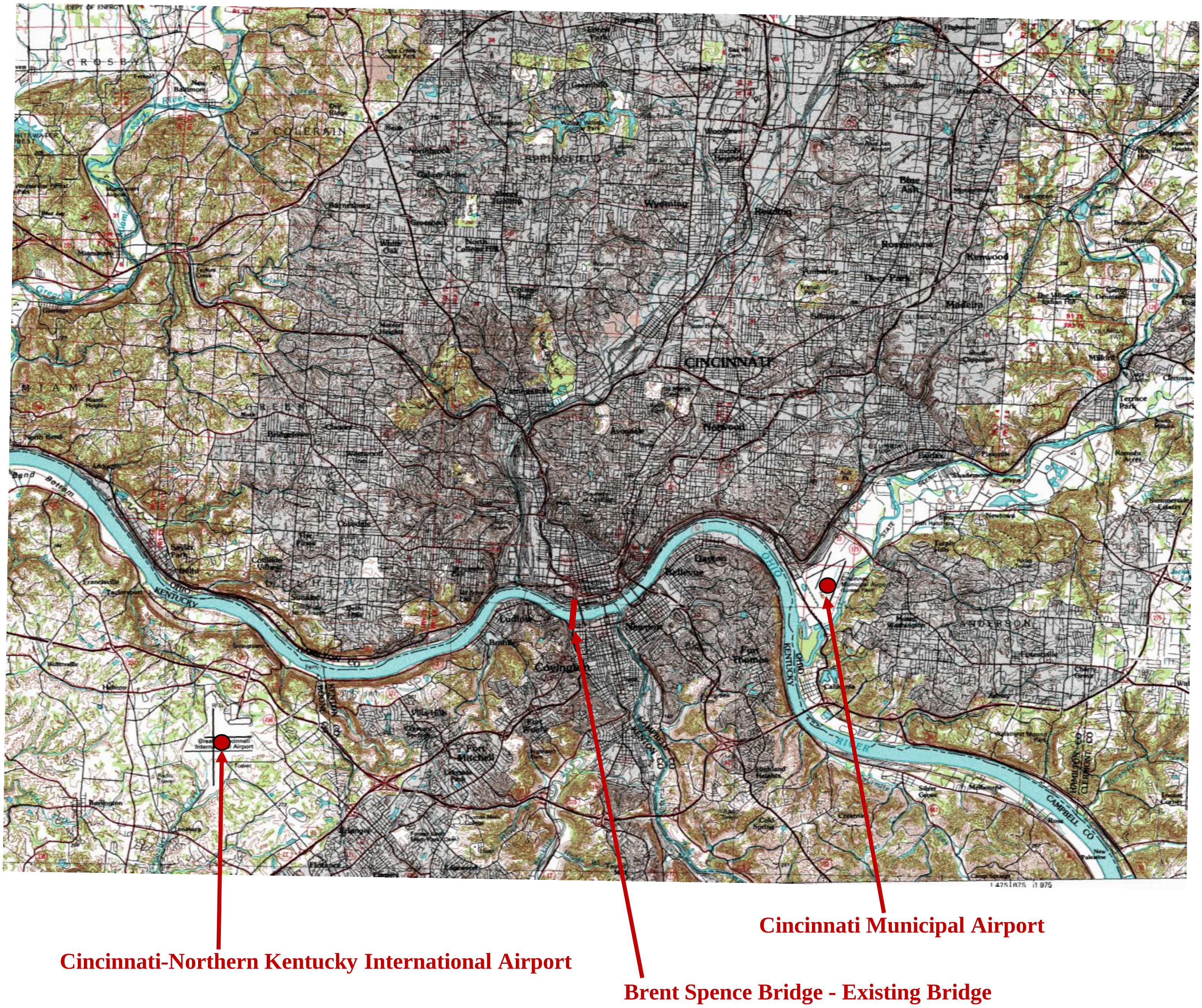
Notes: 1. Given elevation is the approximate average of the two deck elevations at mid-span, above the mean water level

Table 2-2: Turbulence Properties at Deck Level (105 ft above mean water level)

α	I_u (%)	I_v (%)	I_w (%)	${}^xL_u$ (ft)	${}^xL_w$ (ft)	${}^yL_u$ (ft)	${}^yL_w$ (ft)	${}^zL_u$ (ft)
0.17	19.1	15	10.5	1406	117	383	64	232

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

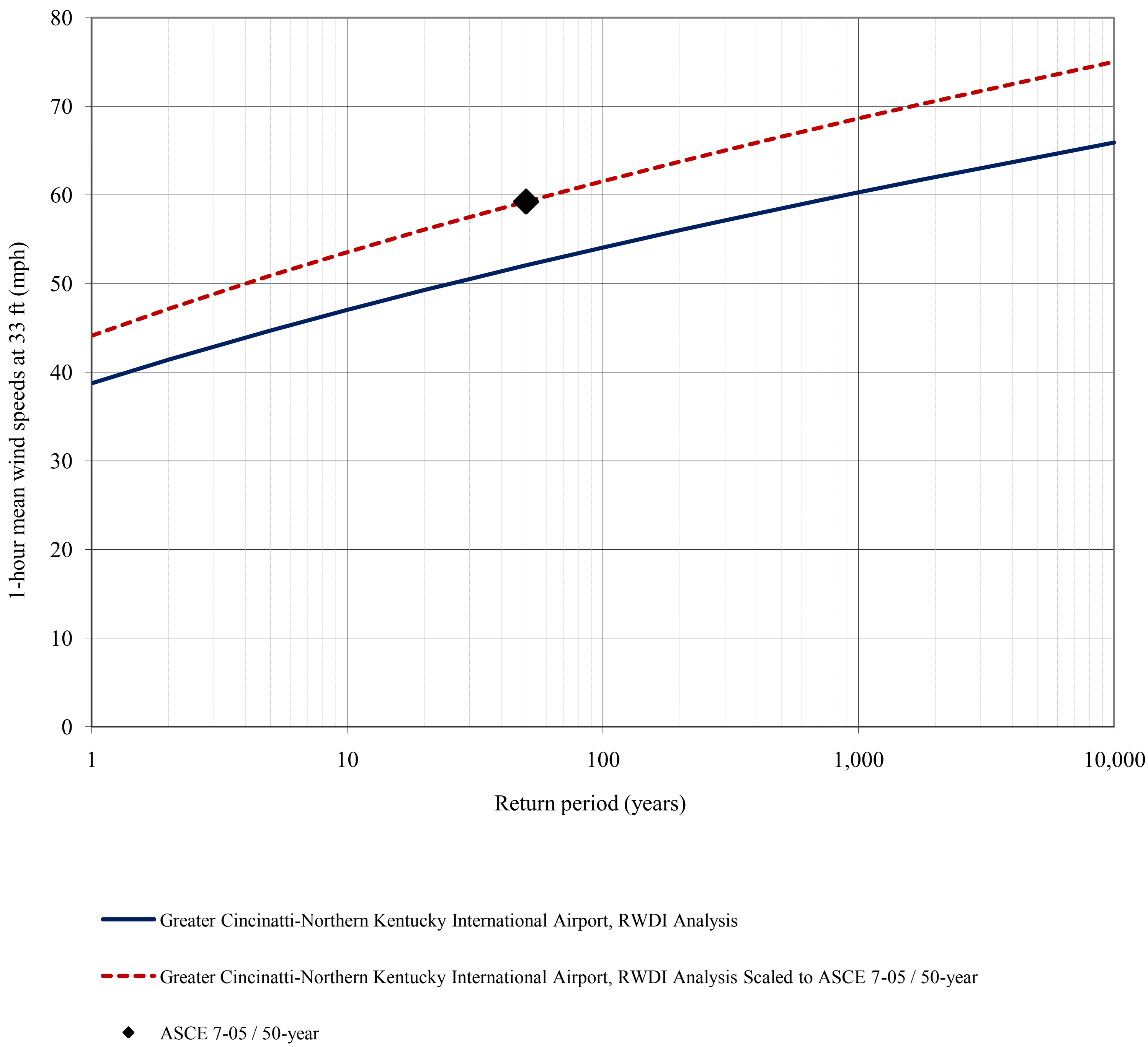
FIGURES



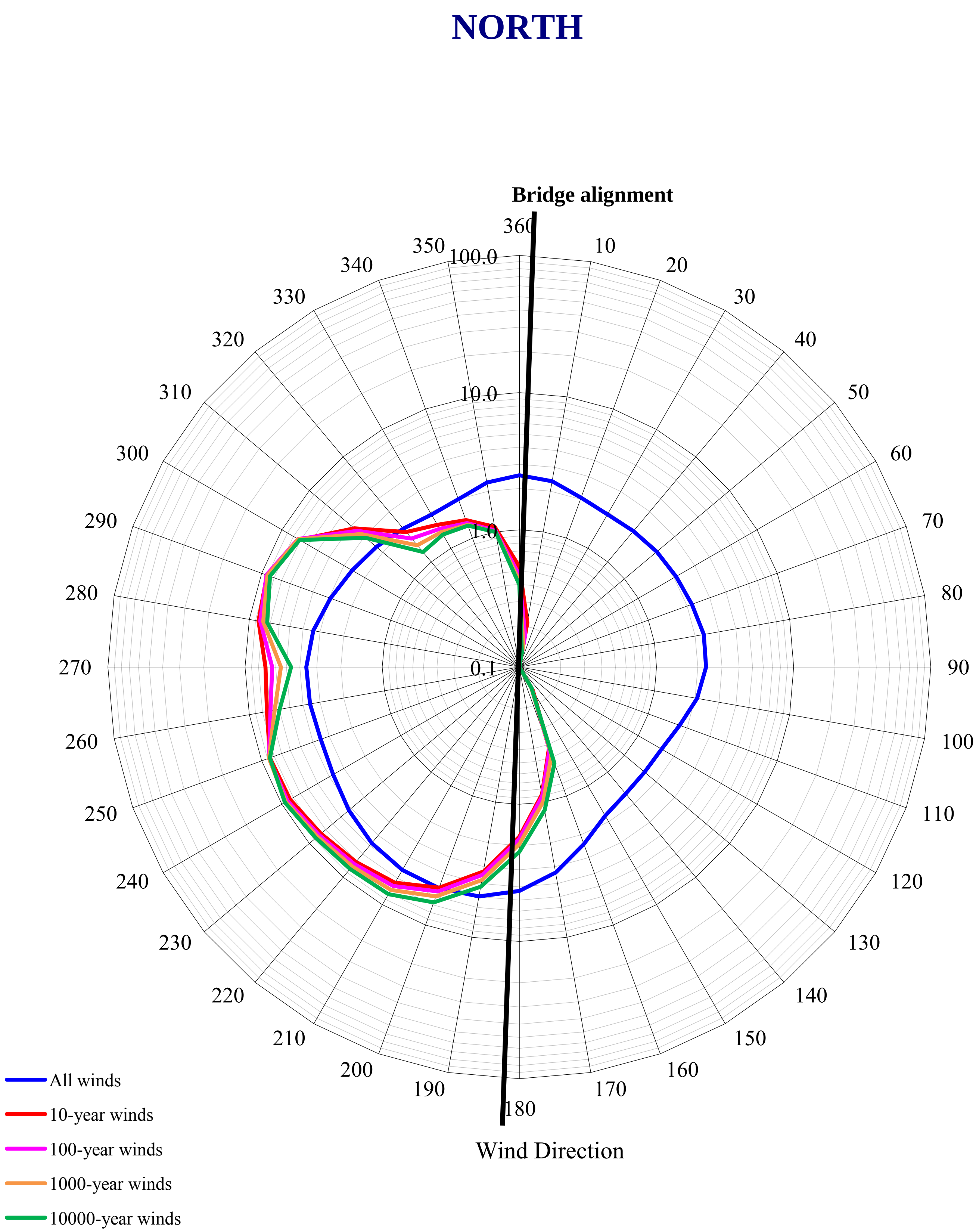
Plan of the Brent Spence Bridge Site Wind Engineering Study Brent Spence Bridge, Cincinnati, OH — Project 0940582	Figure 2-1 August 31, 2010	RWDI

Photographs of the Brent Spence Bridge Site Wind Engineering Study Brent Spence Bridge, Cincinnati, OH Project 0940582	Figure 2-2 July 7, 2010	RWDI

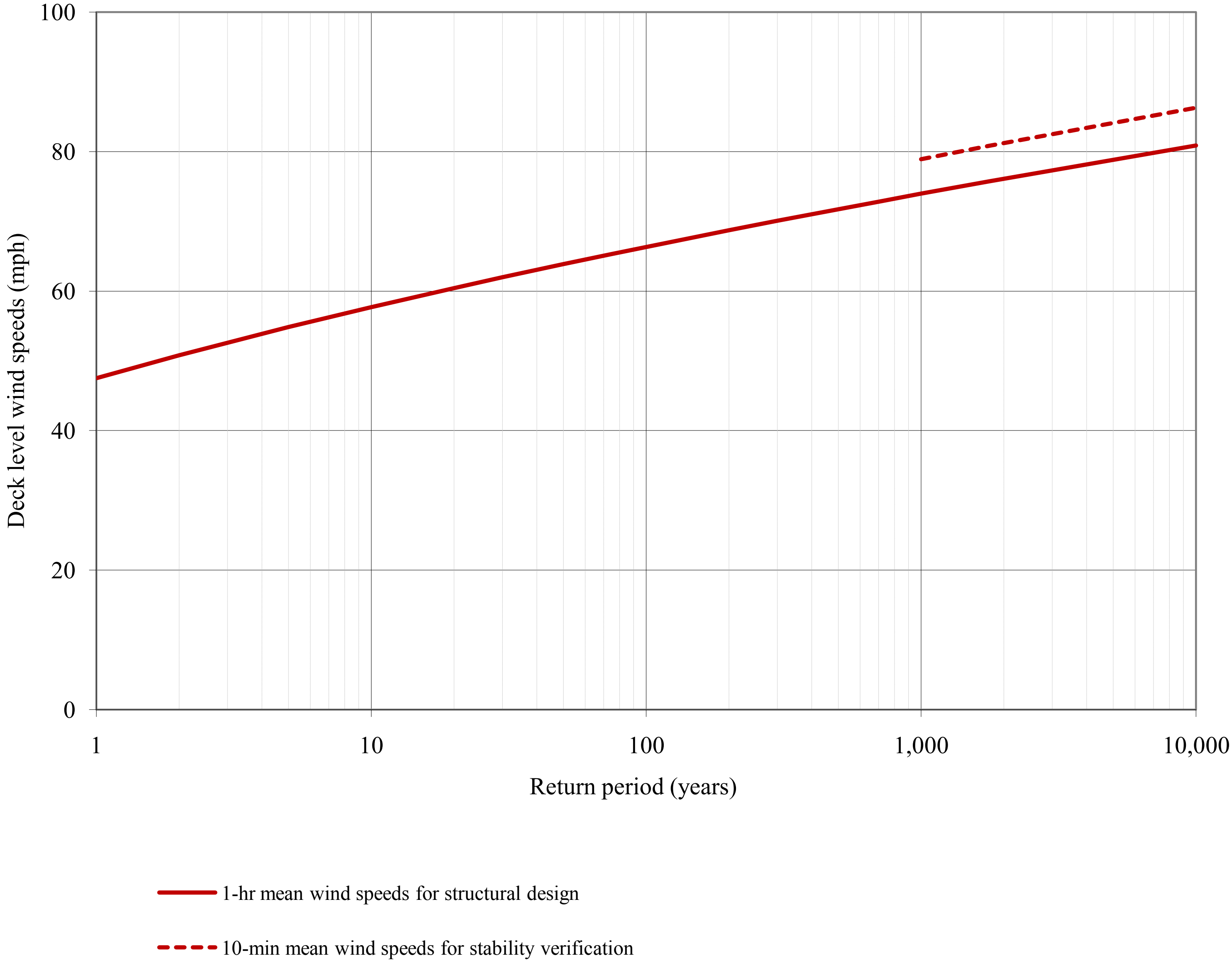
Photographs of the Brent Spence Bridge Site Wind Engineering Study Brent Spence Bridge, Cincinnati, OH Project 0940582	Figure 2-3 July 7, 2010	RWDI



Mean-hourly wind speed at 33 ft for an open terrain Wind Engineering Study Brent Spence Bridge, Cincinnati, OH Project 0940582	Figure 2-4 July 16, 2010	RWDI



Directional distribution of mean-hourly winds at the bridge site Probability (%) of the wind direction for certain return periods Wind Engineering Study Brent Spence Bridge, Cincinnati, OH Project 0940582	Figure 2-5 July 16, 2010	RWDI



Mean wind speed for various return periods **Wind speeds at deck level (105 ft above water level)** Wind Engineering Study Brent Spence Bridge, Cincinnati, OH Project 0940582	Figure 2-6 July 16, 2010	RWDI