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CONSULTING ENGINEERS & SCIENTISTS

Mobile River Crossing

Mobile, AL, USA

Draft Report

Wind Climate Analysis

RWDI # 1600368
July 11, 2016

SUBMITTED TO

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Report	**Releases**	**Dated**
1. Wind Climatology	1st Release to all parties for reviewing	June 30, 2016
2. Project Team	Mike Gibbons, M.E.Sc. Valerie Sifton, P.Eng. Derek Kelly, M.Eng., P.Eng.	Project Coordinator Wind Engineering Specialist Project Manager

EXECUTIVE SUMMARY

Rowan Williams Davies & Irwin Inc. (RWDI) was retained by HDR Inc. to conduct wind engineering studies of the proposed new Mobile River Crossing Bridge project, to be built over the Mobile River in Mobile, Alabama. The current study focuses on:

- The determination of the project required design wind speeds for wind loading and aerodynamic stability verification; and,
- The determination of site specific turbulence properties.

The primary facts and findings of this wind climate study are:

- Recommended wind speeds at deck level of 240 ft
    - 82 mph, mean hourly wind speed for a return period of 20 years, applicable for design during construction of the bridge;
    - 113 mph, mean hourly wind speed for a return period of 100 years, applicable for the design of the completed bridge;
    - 141 mph, 10-min mean wind speed for a return period of 1,000 years, applicable for stability verifications during construction; and,
    - 163 mph, 10-min mean wind speed for a return period of 10,000 years, applicable for stability verifications of the completed bridge.

Wind speeds for design do not include any wind directionality reductions whereas for stability verifications, reductions due to wind climate directionality for extreme winds were included.

Site specific turbulence properties were derived as required for the stability and wind loads studies.

1. INTRODUCTION

Rowan Williams Davies and Irwin Inc. (RWDI) was retained by HDR Inc. to undertake comprehensive wind engineering studies for the proposed Mobile River Crossing Bridge project. The proposed bridge will consist of the construction of a cable-stayed bridge over the Mobile River, with a main span length between 1250 ft and 1450 ft.

2. WIND CLIMATE ANALYSIS

2.1 Overview

This section of the report presents the analysis of the wind climate and wind turbulence properties for the Mobile River Crossing Bridge project. The results presented will be used for the testing and analyses of aerodynamic stability and design wind loads. This study also includes recommended design wind criteria following project requirements and current design practice in North America.

2.2 Wind Climate and Site Analysis

Below are established and recommended design wind criteria required for stability analysis and derivation of wind loads for this bridge. References to relevant documents including ASCE 7-10 Standard are also given. Wind speeds were adjusted for the height of the deck as described later in the report.

2.2.1 Sources of Data

The wind statistics used to determine the design wind speeds and directionality at the bridge site were based on the surface wind measurements taken between 1980 and 2015 at the Mobile Regional Airport, located approximately 12 miles to the west of the proposed bridge site. This airport station contains sufficiently long records to perform a comprehensive statistical analysis for normal winds. Figure 2-1 shows the location of the airport in relation to the Mobile River Crossing Bridge. To enhance our knowledge of extreme wind events, in addition to the historical data, a site specific computer simulation of hurricanes was also obtained. This hurricane simulation was provided by Applied Research Associates (ARA), of Raleigh, NC and was generated using the Monte Carlo Simulation Technique. ARA provided data of hurricane passages both at the surface, deck height and upper levels, corresponding to 33 ft, 240 ft and 2000 ft heights, respectively. The wind speeds at deck level were combined with locally recorded data of surface winds, scaled up to the deck level of 240 ft, to develop the wind climate model for this study. The hurricane study is based on a simulation of 300,000 storm years occurring in the North Atlantic basin and considers all storms that came within a 155 mile radius of the project site.

2.2.2 Local Terrain

Care was taken in the analysis of the hourly wind records from the Mobile Regional Airport to account for the effects of the upwind terrain surrounding the airport. Ideally, airport anemometers are installed in the type of unobstructed open terrain that is used as a reference condition by the building codes. It is important to take into account the site effects for every wind direction so as to correct the recorded wind speeds to as close as possible to their true values representing a standard open terrain.

Prior to conducting any analysis of the surface wind speed observations, the effect of upwind terrain roughness and land cover characteristics at the wind instrument, and at the bridge site, were assessed for each wind direction.

The worldwide recognized wind engineering reference ESDU describes a method[1,2] based on earlier work of Deaves and Harris[3] for evaluating changes in the mean velocity profile following changes in ground roughness. This is particularly suited to translate wind speeds between two sites that experience the same winds, but where upwind conditions at the two sites vary. It can also be used to adjust a measured wind speed value to that of the required reference wind exposure such as standard exposures as defined in the Design Codes.

This method was applied to determine the velocity profiles at the location of each airport's wind instrument, and at the Mobile River Crossing site. Photographs of the airports and their surroundings, and satellite imagery were all used to assess the ground roughness changes for each wind direction.

For comparison to code values, the wind speeds were adjusted by wind direction based on the exposure of the anemometer to produce wind speeds that are equivalent to standard open terrain (i.e. Exposure C in ASCE 7-10[4]).

For evaluation of the wind conditions at the bridge site, the wind speeds from the airport were transposed to the bridge site. This was accomplished by using the wind speeds recorded at the airport anemometer, along with the full wind velocity profile for each wind direction. The wind records were then scaled up to gradient height, which is the height above which the roughness elements on the earth's surface have no impact on the wind speed or turbulence. This establishes a regional wind condition independent of terrain.

1 Engineering Sciences Data Unit, Strong Winds in the atmospheric boundary layer, Part 1: Mean Hourly Speeds, ESDU 82026, London ,UK, 1982.

2 Engineering Sciences Data Unit, Strong Winds in the atmospheric boundary layer, Part 2: Discrete Gust Speeds, ESDU 83045, London ,UK, 1983

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

4 ASCE STANDARD, ASCE/SEI-7-10, American Society of Civil Engineers, Minimum Design Loads for Buildings and Other Structures, 2010.

The gradient height wind speed was then scaled down to the deck height of 240 ft on a direction by direction basis, based on the terrain conditions and wind profiles 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.

2.2.3 Analysis

The design wind speeds for the bridge site were determined applying the following:

(i) The joint probability of wind speed and direction for the site was determined based on the available meteorological data and hurricane simulation. The statistical analyses of this wind data produced a mathematical model based on the Weibull probability distribution, which is discussed in Section 2.2.4;

(ii) This mathematical model 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. This method employed the Upcrossing technique, which is discussed further in Section 2.2.5; and

(iii) Extreme Value Analysis (EVA) using a Fisher-Tippet Type I distribution was conducted on all wind records collected at the three airports, and similarly to the results of the hurricane simulation.

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 long-span bridge. To relate the mean-hourly wind speed to the 10-minute mean, the relationship shown in the Durst curve (in Figure C26-5.1 of ASCE 7-10) provided as Figure 2-3 was assumed. According to this curve, a 1-hour mean wind speed can be converted to a 10-minute mean speed by multiplying by a factor of 1.067. Similarly, a 3-second gust speed is higher by a factor of 1.52 than the 1-hour mean speed. Adjustments for other terrain conditions were made using ESDU methodology[5].

2.2.4 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 probability distribution. This distribution expresses the probability of the wind speed at a given elevation exceeding a value U as

5 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.

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

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 smooth transitions. This "double" fitting was applied in modeling the data from the three meteorological stations for normal winds, whereas single fit Weibull parameters derived for the ARA data were applied to hurricane winds.

From the probability distributions given by Equation (2-1), the overall probability of wind speed was obtained by summing over all wind directions for both the extra-tropical wind conditions derived from the historical record, and the hurricane wind conditions derived from the Monte Carlo simulation.

$$P(U) = (1 - f_H) \cdot P_E(U) + f_H \cdot P_H(U) = \sum_\theta[(1 - f_H)P_{\theta E}(U) + f_H P_{\theta H}(U)], \quad (2\text{-}2)$$

where the subscript E refers to extra-tropical or non-hurricane winds, the subscript H refers to hurricane winds, and f_H. is the fraction of time that there are hurricane winds.

At 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 at the airport station 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 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.

Whereas the 36 years of data (1980-2015 from the Mobile Regional Airport) are assumed sufficient in representing synoptic wind events, they may not contain enough extreme records of hurricanes. Therefore hurricane winds were simulated numerically and applied to improve the predictions at higher return periods. By combining both normal winds and hurricane simulation data, a function representing wind speed vs.

return period was generated and presented in Figure 2-4. In this figure, wind speeds are given as 3-sec gusts at an elevation of 33 ft in standard open terrain.

2.2.5 Upcrossing Method to Determine Directionality Effects on Design Winds

By adapting random noise theory to meteorological data (Rice[6]), it can be shown that the return period, R, in years of a given gradient wind speed, U, can be determined from the Weibull distribution discussed in Section 2.2.4 by

$$\mathrm{R} = \left[\frac{1}{2}\overline{|\dot{\mathrm{U}}|} \cdot \mathrm{p}(\mathrm{U}) \cdot \mathrm{T_A}\right]^{-1}, \qquad (2\text{-}3)$$

where $\overline{|\dot{\mathrm{U}}|}$ is the average of the absolute rate of change of the hourly values of U with time, T_A is the total number of hours in a year, i.e., $T_A \approx 8766$, and $p(U)$ is the probability density of the Weibull summed across all directions, and relates to the cumulative Weibull distribution in given in equation 2-1 by:

$$\mathrm{p_\theta(U)} = \frac{\mathrm{P_\theta(U)}}{\mathrm{dU}}, \qquad (2\text{-}4)$$

$$\mathrm{p(U)} = \textstyle\sum_\theta \mathrm{p_\theta(U)}. \qquad (2\text{-}5)$$

Since we have two separate Weibull models representing the extra-tropical *(E)* and hurricane *(H)* conditions, equation (2-3) becomes:

$$R = \left[\frac{1}{2}\overline{|\dot{U_E}|} \cdot p_E(U) \cdot (T_A - T_H) + \frac{1}{2}\overline{|\dot{U_H}|} \cdot p_H(U) \cdot T_H\right]^{-1}. \qquad (2\text{-}6)$$

Where T_H is the average number of hurricane hours per year. Equation 2-6 was used to determine the return periods for a series of selected wind speeds. The wind speed corresponding to a required return period (e.g., 20, 100, 1,000 years etc.) could then be determined by interpolation. This method is called the Upcrossing Method and was applied to the meteorological data from the three stations and the ARA Hurricane simulation to determine directional reduction factors discussed further in Section 2.3.2.

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

2.2.6 Extreme Value Analyses to Determine Design Wind Speeds

The meteorological data available from the Mobile Regional Airport (1980-2015) were again employed in this analysis. The peak mean-hourly wind speeds based on a nominal 4-day epoch were extracted using the Method of Independent Storms (Cook[7]). These speeds were fit to a Fisher-Tippet Type I distribution, which is given by

$$P(\widehat{U}) = \exp\left(-\, exp\left(-a(\widehat{U} - b)\right)\right), \tag{2-7}$$

where $P(\widehat{U})$ is the probability that the annual peak velocity will not exceed the value, $\widehat{U}$ is the peak velocity, $1/a$ is dispersion and b is the mode.

As described by Harris[8], traditional methods of extreme value analysis typically include fitting monthly or annual maxima to an extreme value distribution. Harris also states that using the Method of Independent Storms in lieu of the monthly or annual maxima increases the number of wind speed maxima used in the extreme value fitting considerably, which ultimately provides greater accuracy in the prediction of the extreme wind speeds.

The size of the hurricane simulation dataset allows for an extreme value analysis of the winds to be conducted without fitting the wind speed data to a particular statistical distribution. Each wind speed is given a rank based on its magnitude. The wind speed probability distribution, $P_t(v > V)$, is given as:

$$\mathrm{P_t(u > U) = 1 - \textstyle\sum_{x=0}^{\infty} P(u > U|x) \cdot p_t(x)}, \tag{2-8}$$

where t denotes the return period in years, $p_t(x)$ is a Poisson process defined as the probability that x storms occur during the time period t, and $P(u > U|x)$ is the probability that velocity u is less than U given that x storms occur.

2.3 Results

According to the wind map on Figure 26.5-1A of the ASCE 7-10 Standard, the basic speed for this region is 163 mph 3-sec gust, corresponding to a return period of 1,700 years. Figure 2-4 shows the 3-sec gust wind speeds in open terrain at elevation 33 ft recommended for the bridge site, the extreme value analysis of the data from Mobile Regional Airport, the extreme value analysis of the ARA hurricane simulation and

[7] Cook, N.J., Towards Better Estimation of Extreme Winds, *J. Wind Eng. Ind. Aerodyn.*, Vol. 9, pp 295-323, 1982.

[8] Harris, R.I., XIMIS, a penultimate extreme value method suitable for all types of wind climate, J. Wind Eng. Ind. Aerodyn., Vol 97, pp 271-286, 2009.

the ASCE 7-10 recommended speeds at return periods ranging from 10 to 1,700 years. The proposed curve for design in this study is based on the combined probability of the historical and hurricane extreme value analyses. It agrees well with the values from ASCE 7-10 for all return periods considered. Based on the analysis completed by RWDI and described herein, it is recommended that the combined historical and hurricane distribution be used as the basis for design. This recommendation is in accordance with 26.5.3 of ASCE 7-10.

2.3.1 Wind Speeds at the Bridge Site

Figure 2-5 shows various wind speeds at a deck level of 240 ft as a function of return period. This figure presents the following information:

- mean-hourly speeds at deck level for return periods from 1 to 10,000 years derived from the meteorological data described in Section 2.2, uncorrected for wind directionality; and,
- the 10-minute mean wind speed for return periods from 1,000 and 10,000 years with and without wind directionality.

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

2.3.2 Wind Directionality Effects

The relative probabilities of exceeding various mean wind speeds from within each of thirty six direction sectors are shown in Figure 2-6. The curves show the probability of exceeding wind speeds with 20, 100, 1,000 and 10,000 year return periods as a function of wind direction. Also the probability of "all winds" (i.e., of any speed) is shown. The proposed bridge main span axis is oriented approximately parallel to the southwest/northeast direction. Therefore, winds normal to the spans would blow from approximately north-west and south-east. Figure 2-6 shows that the most probable directions for strong winds (e.g., once in 100 years) are from the east-northeast. 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. This, combined with the above-mentioned alignment of strong winds, indicated to us that no directionality reduction can be applied to the winds applicable for bridge design and this is in accordance with current design practice of North America.

Figure 2-6 shows that the most probable directions for very high return periods (e.g., once in 10,000 years) are from the east-northeast and south. There is evidence (Irwin and Schuyler[9]) that flutter instability is essentially a function of the wind velocity component normal to the span. Therefore, directionality reduction factors may be applied to the wind speeds for stability assessment of the bridge.

2.3.3 Terrain at the Bridge Site

The terrain surrounding the bridge site is a combination of open water, suburban and urban terrain. As an approximate approach to assess the terrain effects, the ESDU method was used. The suburban and urban areas were taken as having roughness lengths in the range of z_0 = 0.7 ft to 1.0 ft. The roughness lengths of the water fetches were determined as in the range of 0.01 ft to 0.03 ft depending on wind speed. In terms of the traditional power law formula, in which mean velocity varies with height to the power of an exponent α, the value of the exponent ranges from 0.13 to 0.17.

2.3.4 Wind Speeds at Deck Height

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 113 mph at the deck level (Table 2-1). In accordance with typical practices in North America, for the construction phase a 20-year return period is typically referenced for which the estimated mean-hourly speed is 82 mph.

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. Thus the recommended return period is 10,000 years. The typical wind speed averaging time used in bridge studies in North America for assessing aerodynamic instabilities has been 10 minutes. Therefore, the recommended 10,000-year speed is a 10-minute mean value. Using a ratio of 1.067 to scale mean-hourly speeds to 10-minute mean speeds, the design speed for flutter is thus calculated to be 163 mph including directionality effects. For construction, a shorter return period is justifiable due to the shorter length of the construction period, and 1,000 years is recommended. The 1,000-year design flutter speed, arrived at by a similar approach, is 141 mph including directionality effects.

2.3.5 Turbulence Properties at the Bridge Sites

The same ESDU methodology used in determining the wind speeds at the deck level was also applied when estimating the turbulence intensities and length scales at the site. The power law exponent (α), the

[9] 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-206, 1977.

range of roughness length values used (z_0) in determining turbulence properties, turbulence intensities (I_u, I_w, I_v) and length scales (${}^xL_u$, ${}^xL_w$, ${}^yL_u$, ${}^yL_w$, and ${}^zL_w$, parameters required for the buffeting response of long-span bridges to strong winds) are given in Table 2-2.

TABLES

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Table 2-1: Recommended wind speeds at bridge site

Wind Speed Applicable for	Return Period (years)	Mean Wind Speed (mph) at Deck Level 240 ft and Averaging Time		Corresponding 3-sec Gust Speed (mph) at 33 ft Open Terrain
Design during construction	20	82	1 h	93
Design of completed bridge	100	113	1 h	126
Stability during construction	1,000	141*	10 min	147*
Stability of completed bridge	10,000	163*	10 min	170*

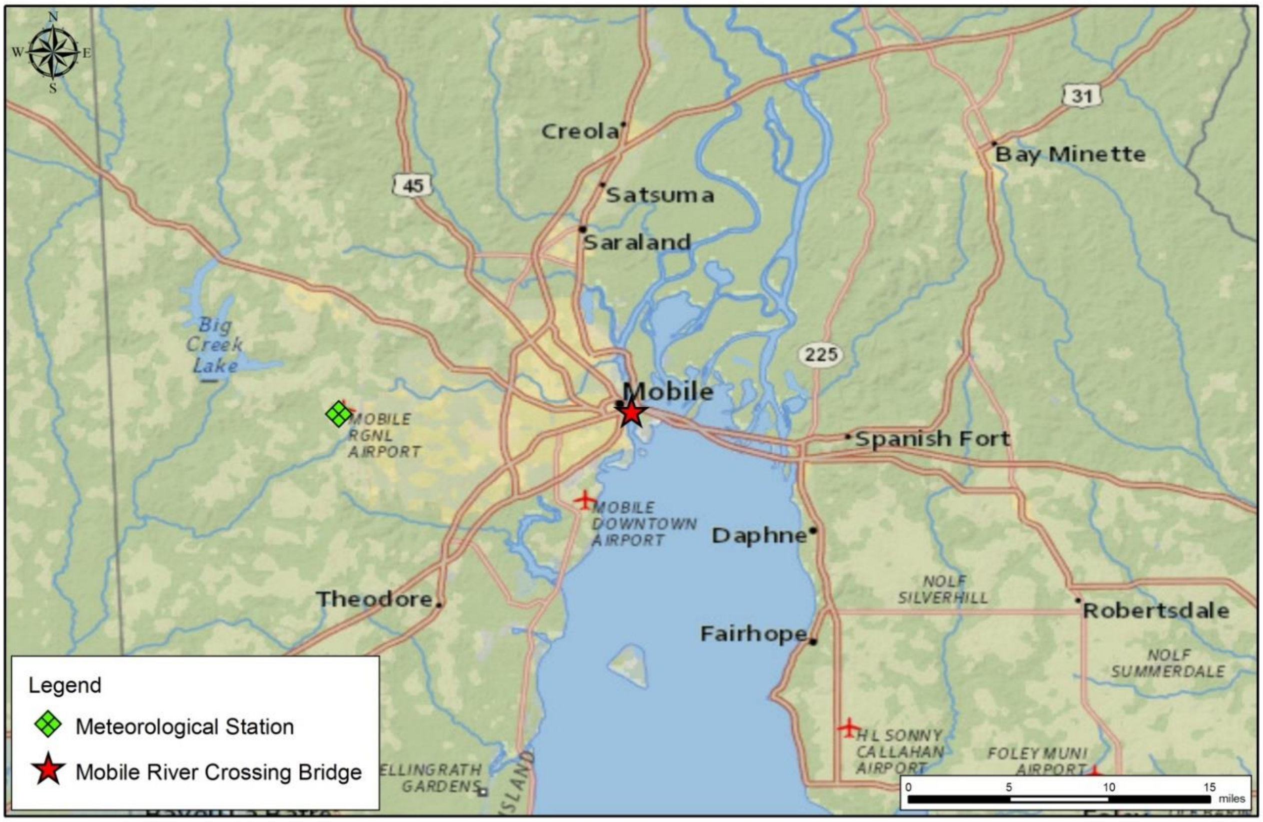
*Includes reduction due to extreme wind climate directionality

Table 2-2: Turbulence properties at deck level of 240 ft

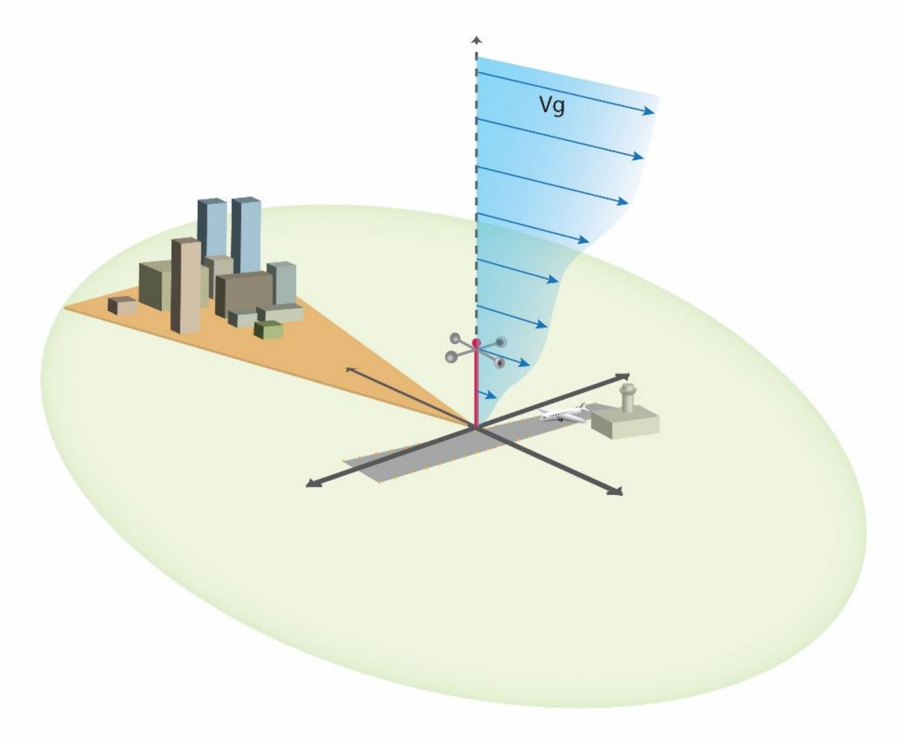
Direction (°CW from N)	z_0 (ft)	α	I_u (%)	I_v (%)	I_w (%)	${}^xL_u$ (ft)	${}^xL_w$ (ft)	${}^yL_u$ (ft)	${}^yL_w$ (ft)	${}^zL_u$ (ft)
150	0.10	0.140	14.0	10.9	7.7	1847	154	511	86	317
330	0.20	0.119	15.3	11.9	8.4	1857	155	513	86	317

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

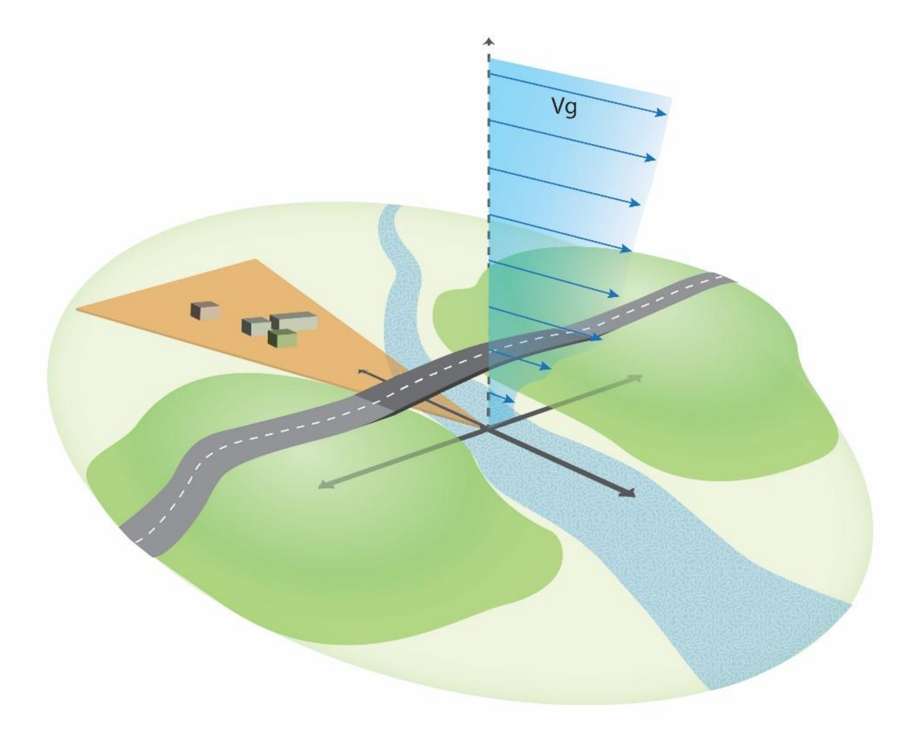
FIGURES



Location of the Mobile Bridge and Airport		Figure No. 2-1
Mobile Bridge – Mobile, Alabama, USA	Project #1600368	Date: June 30, 2016



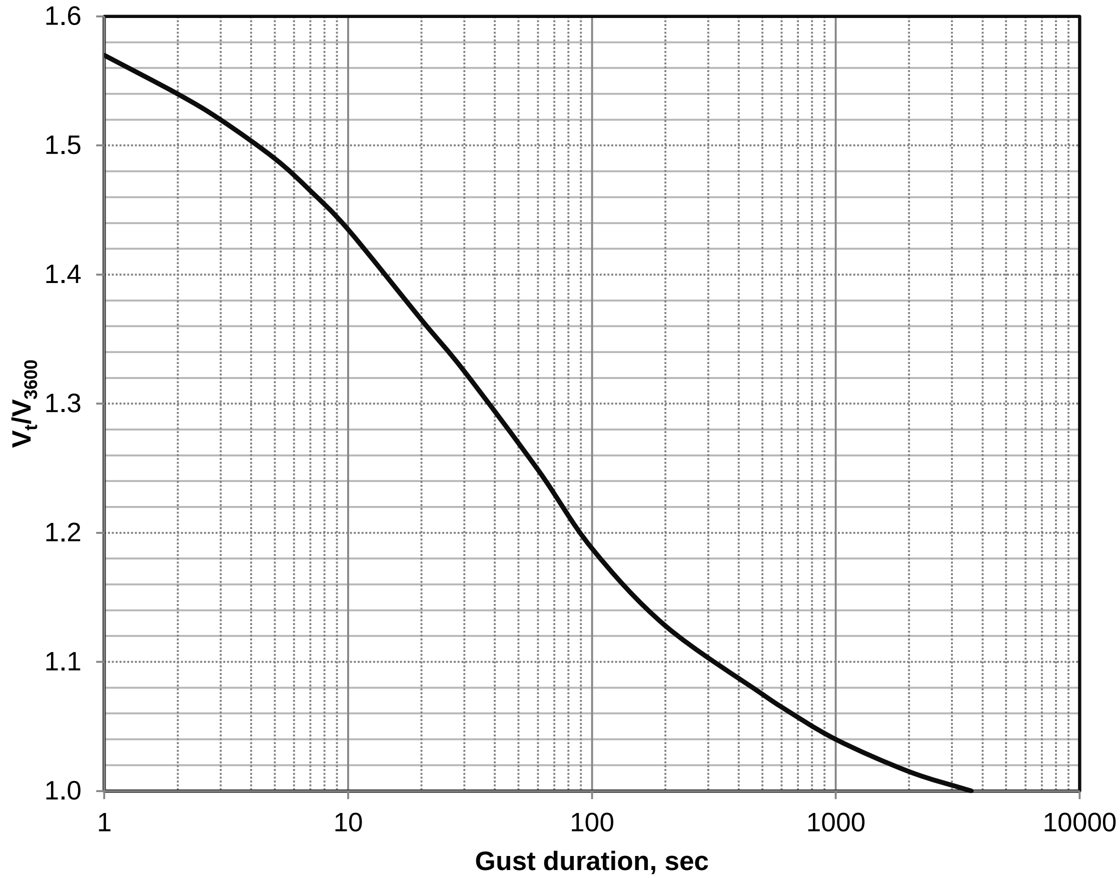
(a) Wind Profile at the Wind Measurement Location



(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 2.2 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 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 Measured Wind Speeds to a Different Location		Figure No. 2-2
Mobile Bridge – Mobile, Alabama, USA	Project #1600368	Date: June 30, 2016

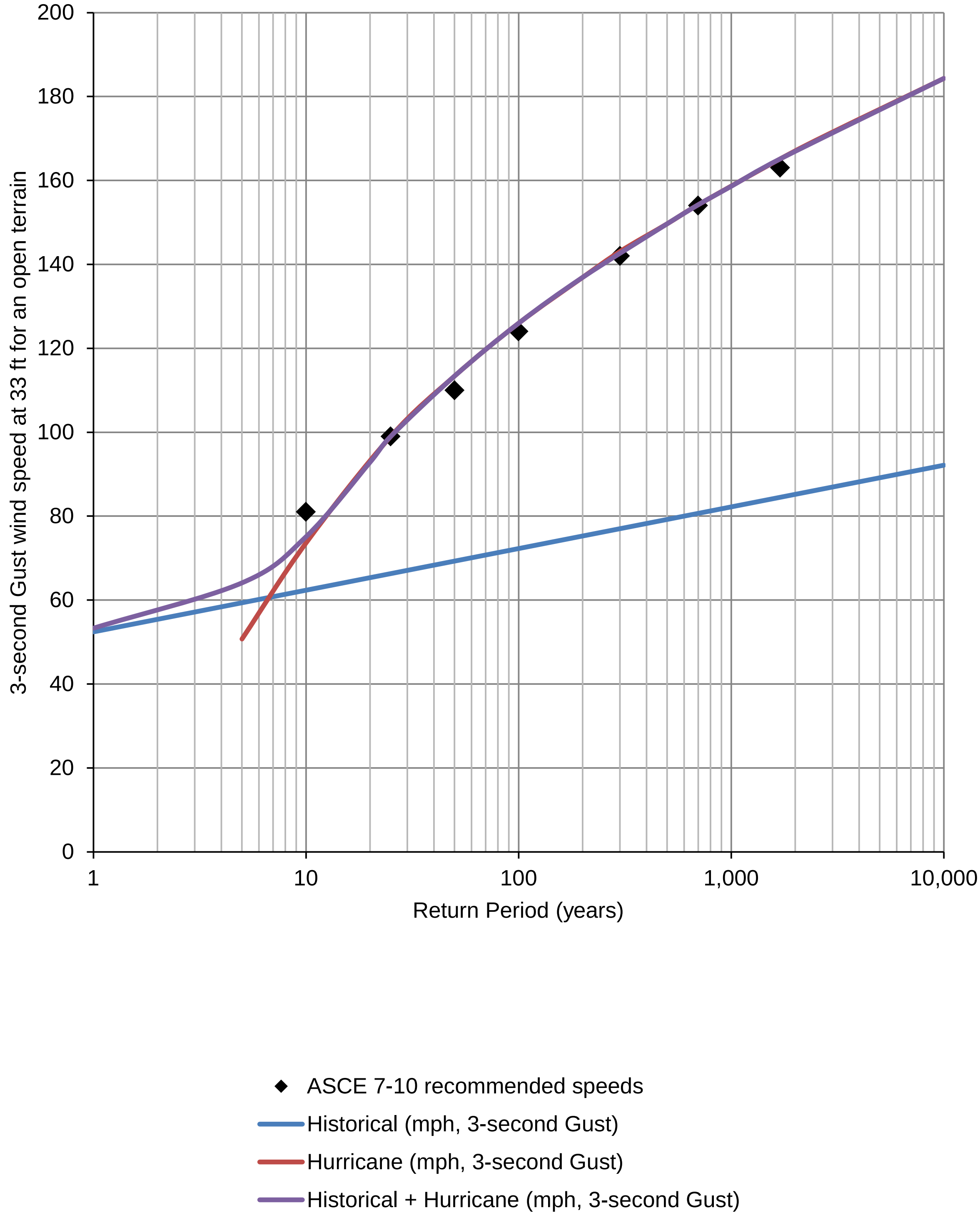


Notes:

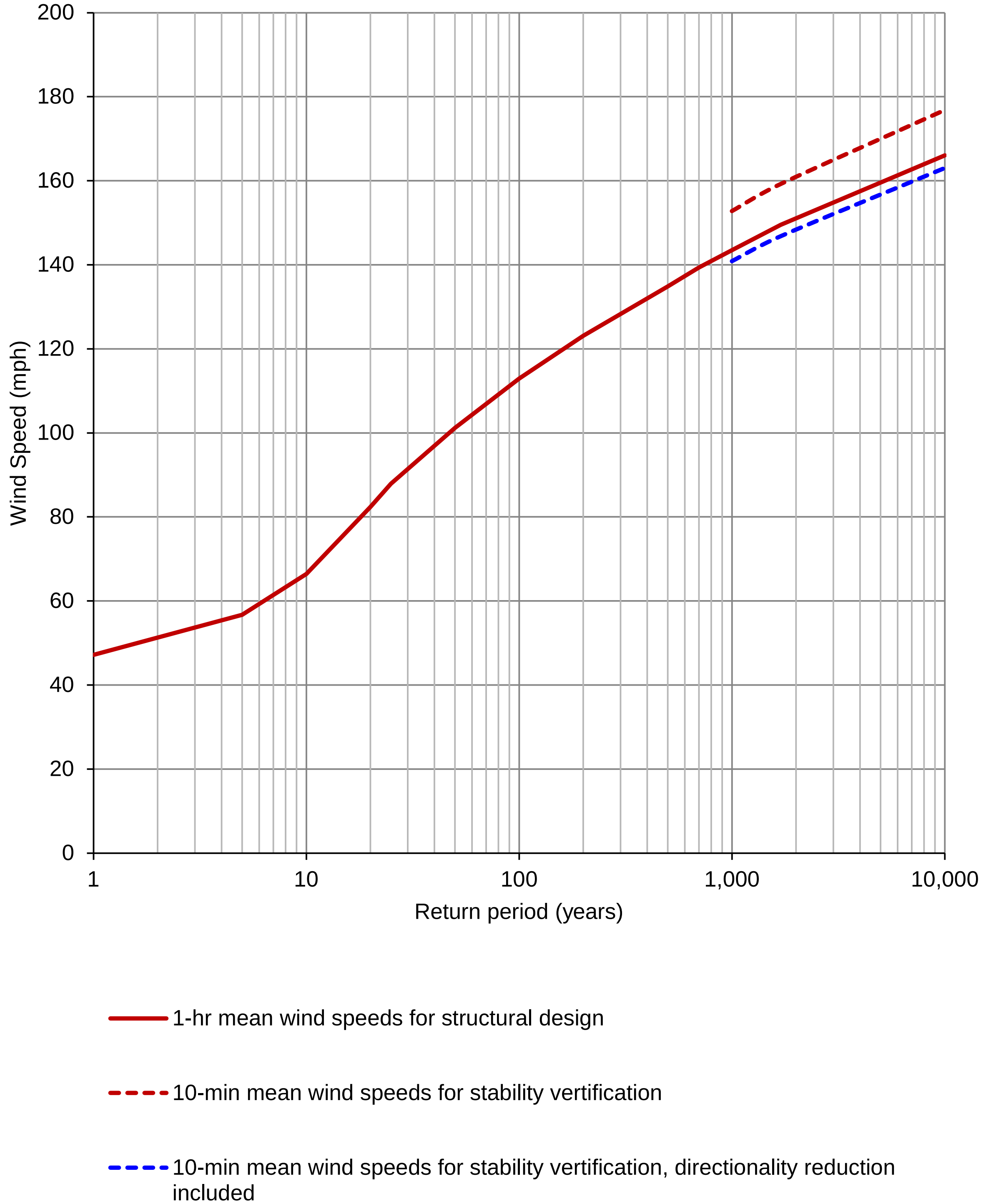
1. From Figure C26-5.1 of ASCE 7-10
2. Gust to mean hourly speed ratios are only valid for open terrain

Gust Speed to Mean Speed Ratio vs Speed Averaging Time	Figure No. 2-3
Mobile Bridge – Mobile, Alabama, USA Project #1600368	Date: June 30, 2016

RWDI



3-second Gust wind speed at 33 ft for an open terrain	Figure No. 2-4
Wind Engineering Study Mobile Bridge – Mobile, Alabama, USA Project #1600368	Date: June 30, 2016



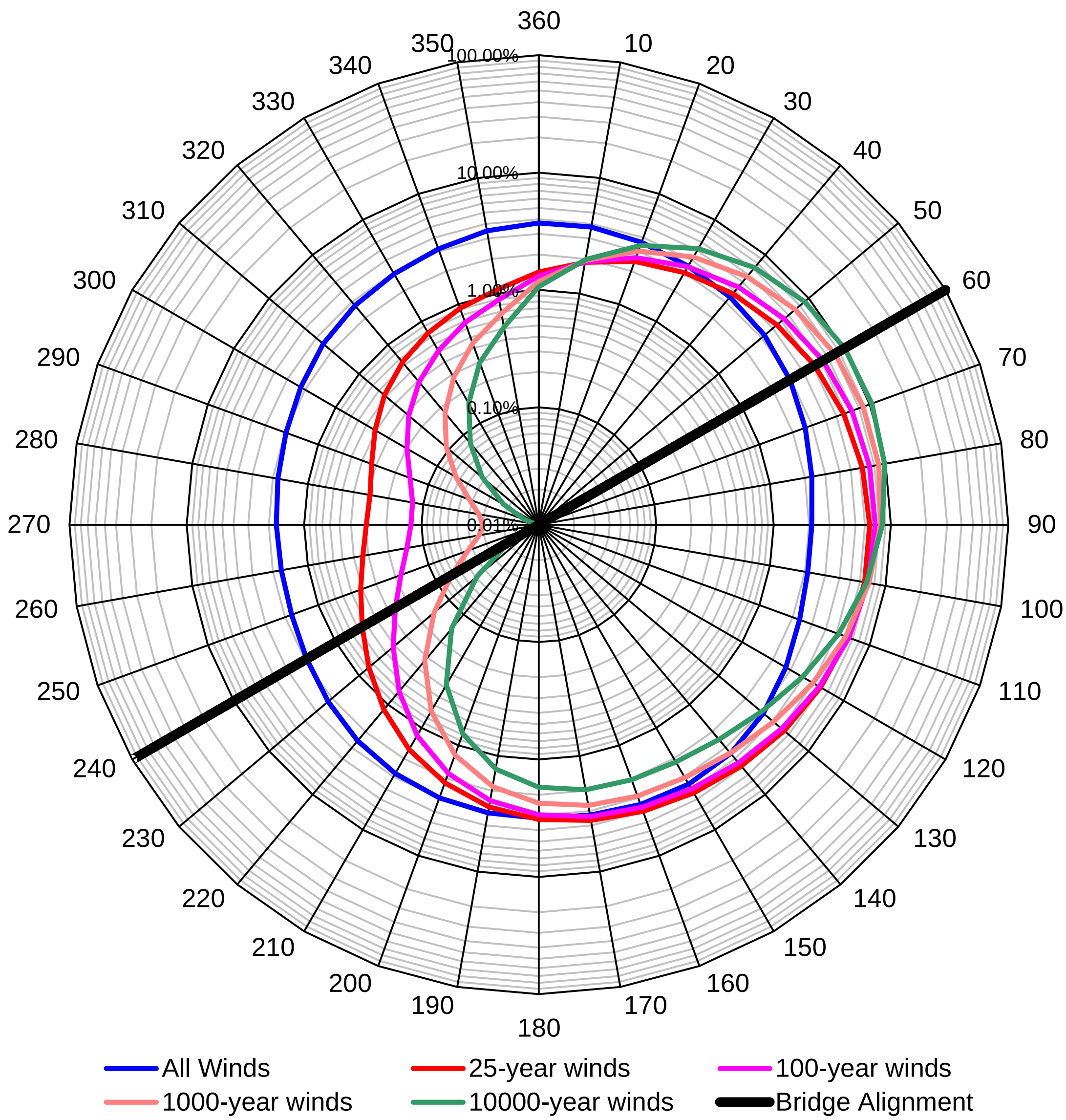
Mean Wind Speed for Various Return Periods
Wind speeds at elevation 240 ft above grade
Wind Engineering Study
Mobile Bridge – Mobile, Alabama, USA

Project #1600368

Figure No. 2-5

Date: June 30, 2016

RWDI



Directional distribution of hourly mean winds at the project site Probability (%) of the wind direction for certain return periods Wind Engineering Study	Figure No. 2-6	
Mobile Bridge – Mobile, Alabama, USA — Project #1600368	Date: June 30, 2016	