MONITORING OF WIND VELOCITIES AND THEIR USE TO STUDY THE WIND-INDUCED STRUCTURAL BEHAVIOR OF THE BALUARTE BRIDGE DURING CONSTRUCTION STAGE

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The great development of new monitoring devices and new processing tools has allowed the conception of innovative monitoring strategies during the construction or service stage of an engineered structure. The construction of special bridges, as cable-stayed bridges, involves numerous activities. This is the case for the construction of one of the tallest bridges in Mexico: the Baluarte bridge. Because of the importance of this bridge, it was decided to carry out a monitoring program during the construction and service stages. The monitoring during the construction stage includes measuring of axial deformations of the pylons, deformations in some of the main steel girders, natural frequencies of different cantilever lengths, tension forces on stays and recording of wind direction and velocities. This paper is focused on the monitoring of wind velocities to study the structural behavior of the bridge during construction and service stages. Of particular interest is the study of the behavior of the bridge under turbulent wind (buffeting effects). For the recording of wind velocities at the site, anemometers were installed in strategic locations along the length of the bridge. In this study, records from these devices are used together with a mathematical model of the bridge to evaluate its behaviour during construction. Further, an estimation of the structural behavior of the bridge is assessed with the mathematical model. The implications of the results are discussed in detail.

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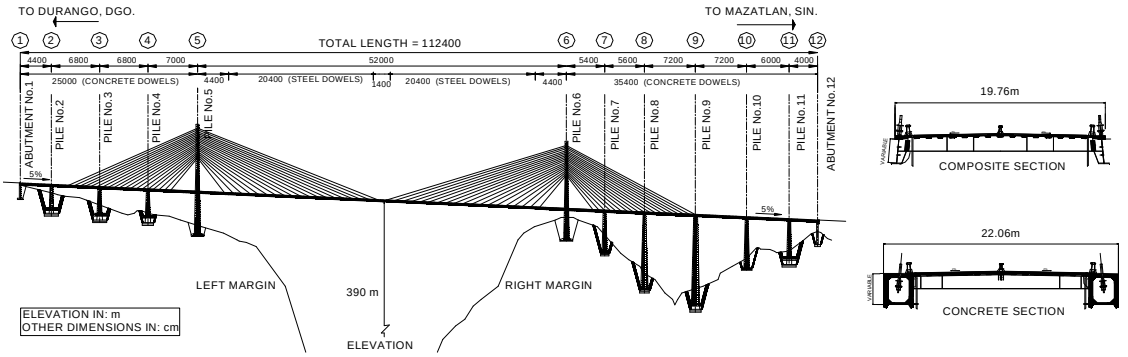
ABSTRACT: This paper is focused on the monitoring of wind velocities to study the structural behavior of a cable stayed bridge during construction and service stages. Of particular interest is the study of the behavior of the bridge under turbulent wind (buffeting effects). For the recording of wind velocities at the site, anemometers are installed in strategic locations along the length of the bridge. Records obtained with these devices are used together with a mathematical model of the bridge to study its behavior during construction. Further, an estimation of the structural behavior of the bridge is assessed with the mathematical model. The implications of the results are discussed in detail.

1 INTRODUCTION

The great development of new monitoring devices and new processing tools has allowed the conception of innovative monitoring strategies during the construction or service stage of an engineered structure. The construction of special bridges, as cable-stayed bridges, involves numerous activities. This is the case of one of the tallest bridges in Mexico: the Baluarte bridge. The construction site is located in the Pacific mountains of Mexico along the Mazatlan-Durango new highway at the border of the Sinaloa and Durango northern states, at approximately 50km from the coast. The bridge will connect a highway through a canyon of about 390m of depth. The construction of the bridge will help to reduce the travelling time between Sinaloa and Durango states, detonating the modernization and commerce in the Northwest of Mexico.

Once completed, the Baluarte bridge will be one of the longest cable-stayed bridge in North America with a total length of 1,124m, composed of a main span of 520m (the longest ever built in Latin America) and two lateral spans of 250 and 354m. The main span has a composite section, while the lateral spans are constructed with prestressed concrete box segments; cross steel beams are used in both types of spans. A total of 76 cables, in a semi-fan layout in two planes, are regularly spaced along 884m of the deck.

The substructure comprises 8 reinforced concrete frame piers, whose heights range from 40 to 140m, approximately; two pylons of the diamond type; and two abutments at the ends . The tallest pylon has a height of 165m, while the other one has a height of 147m. Figure 1 shows a general view of the Baluarte bridge and cross sections of the superstructure.



(a) (b)

Figure 1. The Baluarte bridge: (a) General view; (b) cross sections of the superstructure.

Due to the importance of this structure, a strict control in all the stages that involve the construction of the bridge was implemented, including structural monitoring. An important part of such control is the evaluation of the structural behavior of the bridge during construction and service stages. During the construction stage, the bridge will be subjected to external loads such as wind loads, seismic loads, temperature effects, among others. The monitoring during the construction stage includes measuring of axial deformations of the pylons, deformations in selected steel girders, natural frequencies of different cantilever lengths, tension forces on stays and recording of wind direction and velocities. With the aim of studying the response of the bridge under wind loading during the construction, the second section of this work describes the implemented monitoring plan; the mathematical model of the bridge is described in section three, followed by the analysis and results. The implications of the results in the structural behavior of the bridge are discussed in detail in the conclusions.

2 MONITORING OF WIND VELOCITIES AND DIRECTIONS

2.1 Location of the anemometers

Due to the intricate topography at the site of construction, it was decided to monitor wind velocities at different places around the ravine. Figure 2 shows a sketch with the locations of the meteorological towers where weather stations at different heights (10, 20 and 40m), with respect to ground level, were placed to register wind velocities, among other climate parameters.

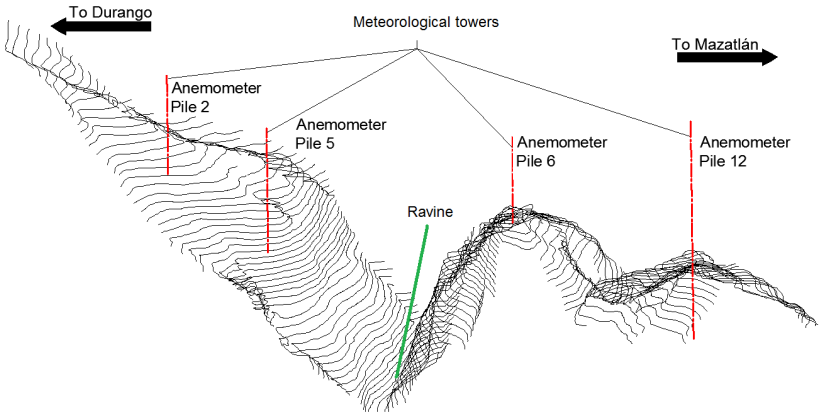
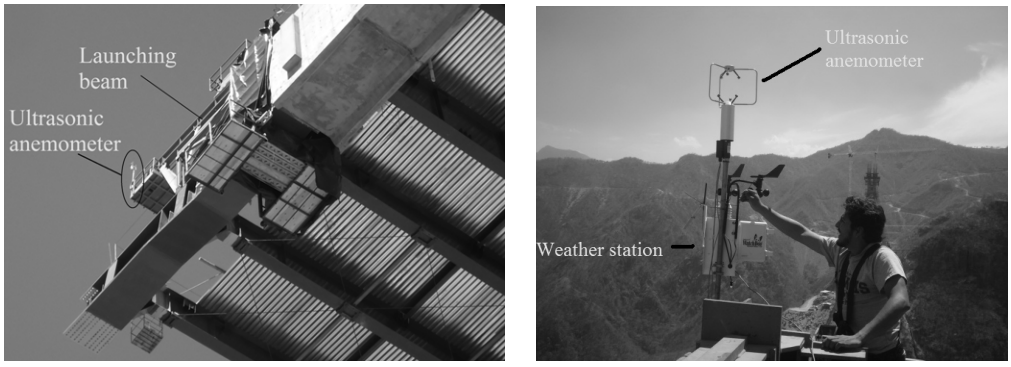


Figure 2. Three dimensional view of the ravine and location of anemometers.

On the other hand, in order to monitor wind velocities during the construction of the main span, a weather station and an ultrasonic anemometer at the top of the launching beam were installed, as shown in Figure 3, as well.



(a) (b)

Figure 3. Ultrasonic anemometer: (a) Placed at the launching beam; (b) installation.

Some of the specifications of the weather stations and the ultrasonic anemometer, employed in the monitoring, are shown in the following table.

Table 1. Specifications of weather stations and ultrasonic anemometer.

Parameter	Weather station	Ultrasonic anemometer
Wind speed	0 - 175 mph	0 - 90 mph
Wind direction (Azimuth)	2° increments	0 – 359.9°
Temperature	-20° to 70°C	-50 to 50°C (Sonic temperature)
Relative humidity	20% to 100% @5° to 50°C	-

Sampling rate	1/60Hz	10Hz

2.2 Recording of wind velocities and directions

The monitoring of wind velocity and direction with the weather stations (see Figure 2) started in June 2008 and continues up to date. The ultrasonic anemometer and the weather station placed at the launching beam started to register wind velocity and direction in May 2010, about the time when the construction of the superstructure was initiated. Recording rate of weather stations can be as small as one sample per minute, whereas the ultrasonic anemometer can be activated manually to register 10 minute records or wind velocity and direction with a sampling rate of 10 Hz. The ultrasonic anemometer measures the three components of wind velocity (two horizontal and one vertical) and the azimuth. It is noted that the weather station placed at the launching beam is employed to compare the magnitude of the wind velocity to that obtained with the ultrasonic anemometer. The following figure presents a comparison of the wind velocity and direction obtained with the weather station and the ultrasonic anemometer. It is observed from the figure that the results are comparable, except that the ultrasonic anemometer captures the energy content in the recording data related to the inertial range (where civil structures stand). The location of the ultrasonic anemometer with respect the bridge is also presented in the same Figure 4.

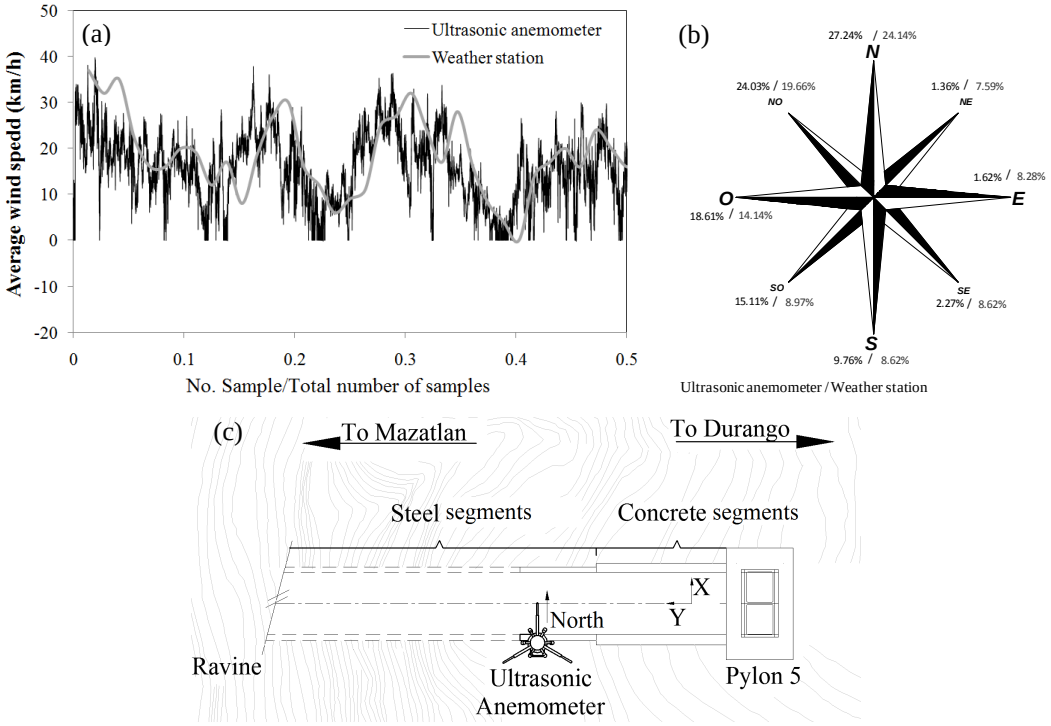


Figure 4. Comparison of the wind velocity and direction: (a) Wind speed records; (b) direction;

(c) location of the ultrasonic anemometer with respect the bridge.

With the purpose of verifying the wind power spectrum (turbulence spectrum) associated to each of the orthogonal components of the wind velocity recorded by the

ultrasonic anemometer, the normalized power spectral density function of selected records of wind speed was estimated by Welch's method (Welch, 1967) and is presented in Figure 5. Davenport's spectrum of turbulence (Davenport, 1964) for the longitudinal component is also shown in the same figure.

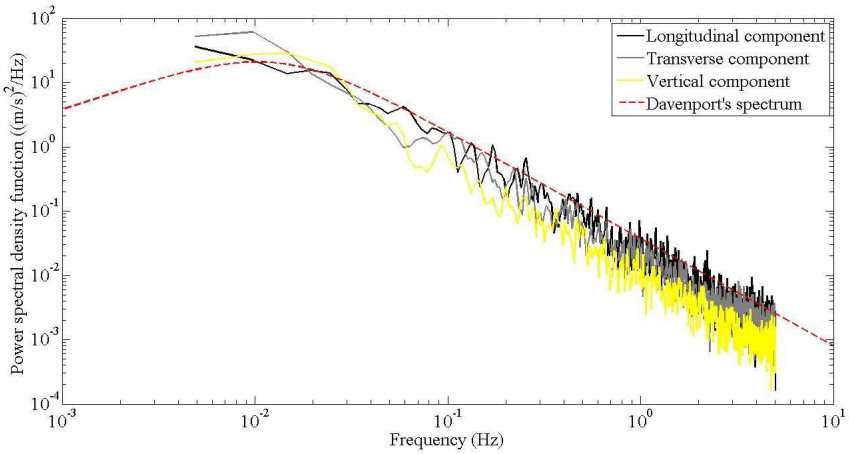


Figure 5. Normalized power spectral density function of turbulent wind records.

Figure 5 shows a good agreement between the longitudinal component of turbulent wind and Davenport's spectrum. This fact is advantageous, since other power spectral density functions for turbulent wind given in the literature can be used to simulate turbulent wind records or forces with similar characteristics (energy and frequency content) as the ones recorded at the construction site. It is also observed in Figure 5 that, as expected, the energy content of the traverse and vertical components is less compared to that of the longitudinal component.

The following section describes the mathematical model developed for the study of the structural behavior of the bridge under wind forces during the construction stage.

3 MATHEMATICAL MODEL OF THE BALUARTE BRIDGE

Figure 6 presents the finite element model of the Baluarte bridge. It was developed in the program SAP2000 using standard beam elements to model the superstructure and substructure.

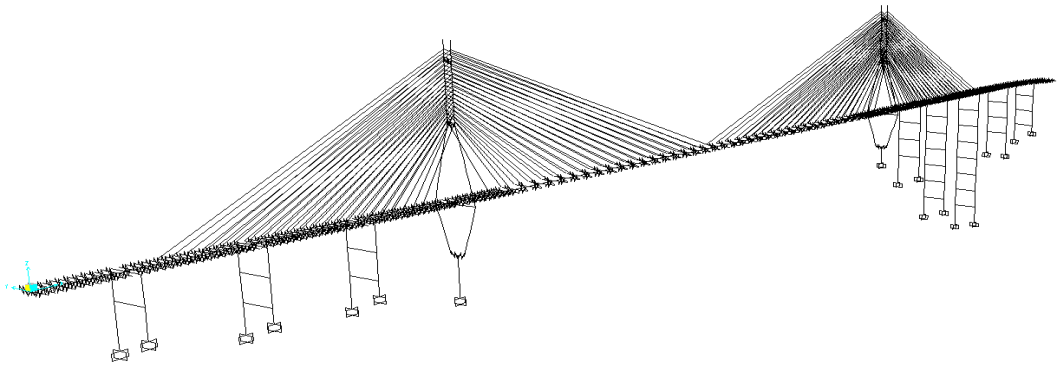


Figure 6. Finite element model of the Baluarte bridge.

To account for the geometrical nonlinear behavior due to the cable sag, cables were modeled as truss elements and characterized with the modulus of Ernst (Ernst, 1965). Piers and towers were fixed at the base. The deck was modeled with beam elements and characterized with the properties of the actual dowels/segments (i.e., area, inertia and torsional constant).

Dynamic analyses were carried out to estimate the modal shapes and frequencies; the following table summarizes the first four modal frequencies of the bridge.

Table 2. Modal frequencies of the Baluarte bridge.

Mode	Frequency (Hz)	Shape
1	0.25	Lateral
2	0.30	Vertical
3	0.39	Lateral
4	0.44	Lateral

The dynamic properties obtained with the mathematical model can then be used to complement experimental results from ambient or pull-back vibration tests and identify possible changes in the dynamic properties due to the influence of fatigue, prestress losses, corrosion, etc

4 STRUCTURAL BEHAVIOR OF THE BALUARTE BRIDGE DURING CONSTRUCTION STAGE UNDER WIND FORCES

4.1 Description of the analysis

To study the structural behavior of the Baluarte bridge under wind loads during construction, a parametric analysis was carried out. Preliminary results are presented in this paper. The construction stages (cantilever lengths) considered, are shown in Figure 7.

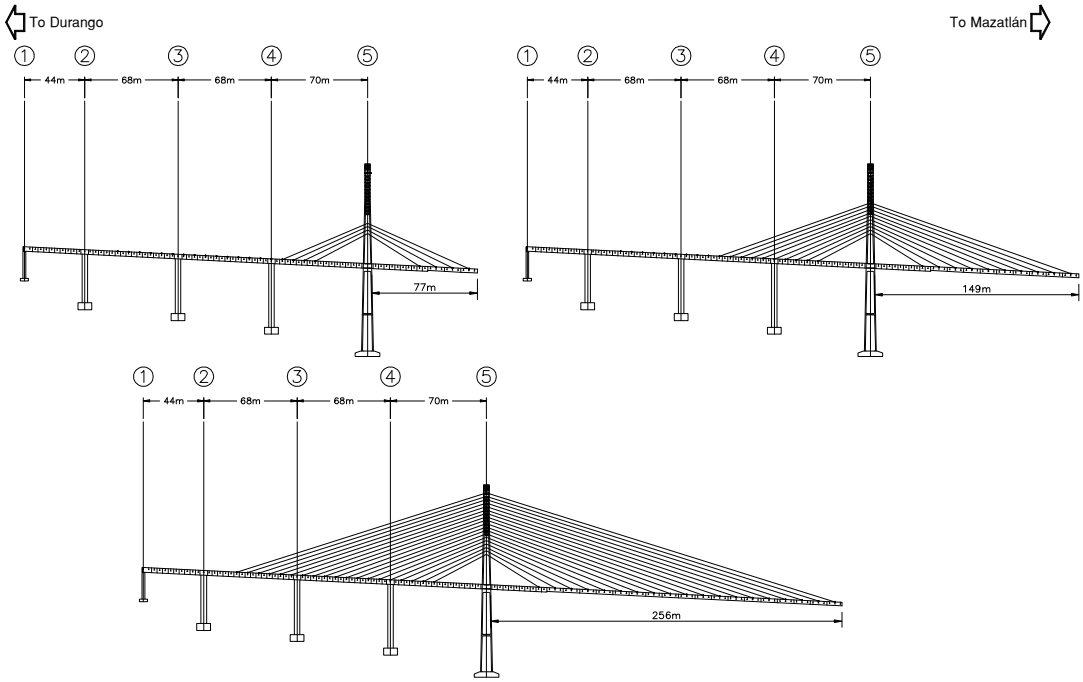


Figure 7. Construction stages analyzed.

As observed in Figure 7, each construction stage considers different cantilever lengths (from 77 to 256m) with different dynamic properties.

In order to define wind actions on the cantilevers, turbulent wind speeds were simulated along the cantilever length. Each of these wind speeds were characterized, in terms of energy content, using the wind records obtained with the ultrasonic anemometer during the monitoring plan. Wind forces were then estimated with the use of the turbulent wind speeds and applied to the mathematical model of a specific cantilever length. It should be pointed out that the wind speed records obtained with the ultrasonic anemometer are associated with a cantilever length of 77m; however, such records will be used for comparison purposes for the cantilever lengths of 149 and 256m. Once the construction stage reaches such lengths, the results of the analyses can be verified.

4.2 Results of the analysis

The following figure shows the variation of the peak lateral displacement at the tip of the cantilever for each of the construction stages considered, for different mean wind speeds at 10m height and for a 20% longitudinal turbulence intensity. The wind velocities recorded with the ultrasonic anemometer were used to estimate the turbulence intensity at deck height. The reference level of the mean wind speed was 250m below the midpoint of the deck.

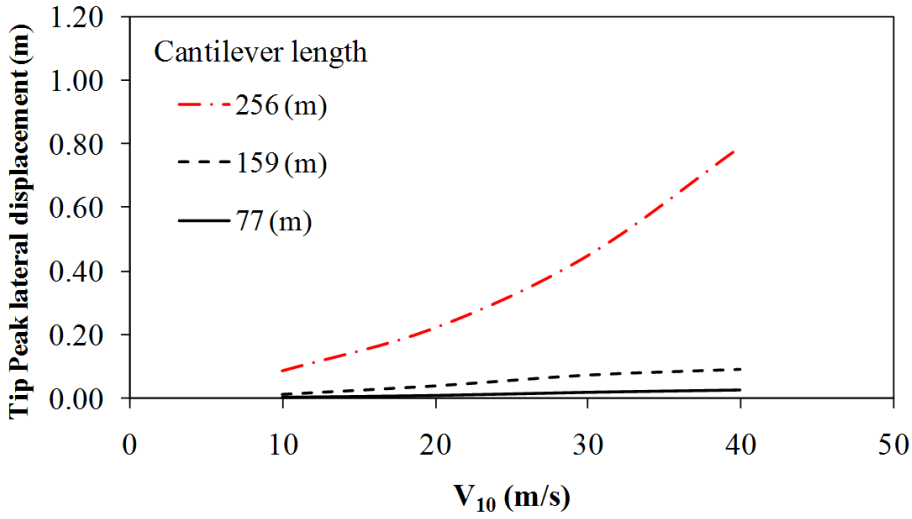


Figure 8. Tip peak lateral displacement for different cantilever configurations.

It is observed in the figure that the response varies nonlinearly with the mean wind speed, and that, as expected, the most critical stage of the cantilever is before the closing of the bridge, where the cantilever length is about 256m as shown in Figure 8. It is important to point out that the results were estimated for a longitudinal turbulence intensity of 20% and that a change in such value would modify the results.

5 CONCLUSIONS

Monitoring of wind velocities at the site of construction of the Baluarte bridge were recorded and used to study the wind-induced structural behavior of the bridge during construction stages. The results of the analyses showed that the most critical stage of the cantilever is before the closing of the bridge, where the cantilever length is about 256m. Some other observations that can be drawn from this study are:

- Monitoring of wind velocities and directions are very useful in the study of the wind characteristics at the site of construction, since they provide the tools to characterize the wind field at the site (i.e., mean wind velocities, turbulence intensities, power spectral density functions, integral lengths and coherences);
- Combination of wind field data and simulations analysis is an alternative to predict the structural behaviour of a particular structure.

ACKNOWLEDGEMENTS

The writers are solely responsible for the facts and contents of this paper. This paper was prepared as part of an agreement funded by the Ministry of Communication and Transportation (SCT). The authors also acknowledge the support and assistance of the technical staff of SCT.

The authors also acknowledge the support and assistance provided by the staff of the Institute of Engineering of the National Autonomous University of Mexico (UNAM).

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