CHALLENGE JOURNAL OF STRUCTURAL MECHANICS 4 (4) (2018) 137–152

Challenge Journal of Structural Mechanics

Research Article

Monitored structural behavior of a long span cable-stayed bridge under environmental effects

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ABSTRACT

An accurate numerical analysis of the behavior of long-span cable-stayed bridges under environmental effects is a challenge because of complex, uncertain and varying environmental meteorology. This study aims to investigate in-situ experimental structural behavior of long-span steel cable-stayed bridges under environmental effects such as air temperature and wind using the monitoring data. Nissibi cable-stayed bridge with total length of 610m constructed in the city of Adıyaman, Turkey, in 2015 is chosen for this purpose. Structural behaviors of the main structural elements including deck, towers (pylons) and cables of the selected long span cable-stayed bridge under environmental effects such as air temperature and wind are investigated by using daily monitoring data. The daily variations of cable forces, cable accelerations, pylon accelerations and deck accelerations with air temperature and wind speed are compared using the hottest summer (July 31, 2015) and the coldest winter (January 1, 2016) days data.

ARTICLE INFO

Article history:
Received 6 August 2018
Revised 21 September 2018
Accepted 12 October 2018

Keywords:
Long span cable-stayed bridges
Environmental effects
Temperature effects
Wind effects
Monitoring of bridges

1. Introduction

The number of constructed long span cable-stayed bridges has increased over the last few decades in the World. These bridges have a complicated structural system because their main structural elements including decks, towers (pylons) and main cables have different structural characteristics. The cable-stayed bridges inevitably suffer from traffic loads and even natural disasters, such as earthquakes and typhoons. In addition to, the cable-stayed bridges are subject to daily, seasonally, and annually varying environmental effects such as air temperature, humidity, wind etc. It has been seen that structural behavior of bridges is more significantly affected by environmental thermal effects than by external operational loads (Zhou et al., 2016). Therefore, the importance of the bridge structural monitoring is highlighted during their service life. Because, structural monitoring systems installed on cable-stayed bridges have the potential to generate large data repositories from which a deeper understanding of bridge behavior can be obtained under environmental effects.

Structural health monitoring of bridges using environmental-induced responses has received increasing attention from researchers. Sohn et al. (1999) prepared an experimental study of temperature effect on modal parameters of the Alamosa Canyon Bridge. They indicated that a linear four-input filter to temperature can reproduce the natural variability of the frequencies with respect to time of day. Peeters and De Roeck (2001) implemented one-year monitoring of the Z24 Bridge. Tong et al. (2001) and (2002) investigated temperature distribution and extreme thermal loading and the design temperature profiles for various types of steel bridge deck with different thickness of bituminous surfacing developed. Fujino and Yoshida (2002) investigated wind-induced vibration and control of Trans-Tokyo Bay Crossing Bridge. It was shown that the results from the field

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ISSN: 2149-8024 / DOI: https://doi.org/10.20528/cjsmec.2018.04.002

and from the wind tunnel tests are fairly consistent regarding the amplitudes and wind speed range of the vortex-induced vibration in the first vertical vibrational mode of the bridge. Lucas et al. (2003) determined the thermal actions on a steel box girder bridge. Mondal and DeWolf (2007) developed a computer-based system for the temperature monitoring of a post-tensioned segmental concrete box-girder bridge. Li and DeWolf (2007) investigated the effect of temperature on modal variability of a curved concrete bridge under ambient loads. The results of the study showed that the variability of measured modal parameters due to temperature should be well understood and quantified prior to the establishment of a baseline for use in damage assessment algorithms. Catbas et al. (2008) implemented structural health monitoring and reliability estimation of a long span truss bridge under environmental data. It was seen that the responses due to temperature have a significant effect on the overall system reliability of long span truss bridges. Xu et al. (2010) monitored temperature effect on a long suspension bridge. The statistical relationship between the effective temperature and the displacement of the bridge was developed by the authors. Kim and Laman (2010) determined integral abutment bridge response under thermal loading. The study revealed that the thermal expansion coefficient, bridge length and pile soil stiffness significantly influence the integral abutment bridge response. Li et al. (2010) identified modal behavior of bridges under varying temperature and wind effects. Xia et al. (2011) determined variation of structural vibration characteristics versus non-uniform temperature distribution. Cao et al. (2011) investigated temperature effects on a cable-stayed bridge using health monitoring data. They expressed that temperature gradient in the steel girder was larger than the design specification. Ding et al. (2012) and Ding and Wang (2013) estimated extreme temperature differences and analyzed thermal field characteristic of steel box girders based on long-term measurement data. It was shown that horizontal temperature differences in top plate and vertical temperature differences between top plate and bottom plate are considerable. Li et al. (2014) investigated field monitoring and validation of vortex-induced vibrations of a long-span suspension bridge. It was found that the inhomogeneity of the wind field along the span-wise direction of the bridge is also a critical factor that affects vortex-induced vibrations of full-scale bridge. Faravelli et al. (2014) investigated the temperature effects on the response of the bridge "ÖBB Brücke Großhaslau". de Battista et al. (2015) measured and modelled the thermal performance of the Tamar suspension bridge using a wireless sensor data. Westgate (2012) and Westgate et al. (2015) investigated environmental and solar radiation effects on suspension bridge performance. They demonstrated that peak temperatures of the suspended structure and cables occur at different times. Yarnold and Moon (2015) determined temperature-based structural health monitoring baseline for long-span bridges. Zhou et al. (2013), (2014) and (2015) investigated thermal load effects on the bridges. The transversal and vertical thermal gradients were developed by the authors. Zhou et al. (2016) performed temperature analysis of a long-span suspension bridge based on field monitoring data. Zhang et al. (2017) performed long-term modal analysis of wireless structural monitoring data from a suspension bridge under varying environmental and operational conditions. The study proposed an automated stochastic subspace identification approach for the extraction of bridge modal properties for the large amount of data. Xia et al. (2013) and (2017) investigated in-service condition assessment of a long-span suspension bridge using temperature-induced strain data. A new structural damage identification method using temperature-induced responses was proposed by the authors and applied to a long-span suspension bridge. Li et al. (2017) performed cluster analysis of winds and wind-induced vibrations on a long-span bridge based on long-term field monitoring data. It was shown that the nonuniformity of the wind speed along the span-wise direction has a significant influence on the vortex-induced vibrations mode.

This study aims to investigate in-situ monitored structural behavior of long-span steel cable-stayed bridges under environmental effects. Structural behavior of main structural elements including decks, towers (pylons) and main cables of a long span cable-stayed bridge under environmental effects such as air temperature, humidity and wind are determined by using daily monitoring data. Nissibi cable-stayed bridge constructed in Adıyaman, Turkey, in 2015 is selected as an example. After structural and monitoring systems of the bridge are briefly introduced, the effects of air temperature and wind speed on the behaviors of cables, pylons and deck are investigated by using monitored forces and accelerations.

2. Nissibi Bridge and Its Structural Monitoring System

The long span Nissibi cable-stayed bridge spans the reservoir of Atatürk Dam on the Euphrates River in South Eastern Anatolia (Bayraktar et al. 2017). The bridge was constructed on the 80th km of the Adıyaman-Diyarbakır highway between 2012-2015 in Turkey. A plan, section and view of the bridge are shown in Fig. 1. The bridge total length is 610m. The 400m main span between the two pylons consists of a 380m long, 26.5m wide and 2.70m height orthotropic steel box section and 20m prestresed concrete deck. The each side of prestresed concrete deck is length of 105m. The structural system of the bridge is founded entirely on rock by means of spread footings. The two invert Y pylons have a structural height of 97.78m from top of footing to the top of pylon. The pylon is made of reinforced concrete except for the top region of the 14-cable stay anchors. The side span piers and abutment are designed as reinforced concrete structures supporting the heavy side span prestressed concrete deck. The cable system consists of the typical 7 wire 0.6" galvanized strand and the cable sizes vary depending on the force in the stay cable. Dampers were installed on some of the cables used in the bridge. The deck is carried by 20 double cables (80 cables in total). The deck is supported by lead rubber bearings located on the pylons, side span piers and abutments for the earthquake protection. In addition to, dilatation joints are used at the beginning and end of the deck. The probability of exceedance of the design earthquake within a period of 50 years was considered as 2% (2475 years) in the seismic analyses. The wind velocity considered in design was 33.6m/s (120km/h).

The monitoring system of the bridge consists of 28 sensors located on the foundations, deck, pylons and cables including load cell, accelerometers, wind, temperature and humidity sensors. Bridge structural monitoring system and some views of the sensors are shown in Figs. 2 and 3.

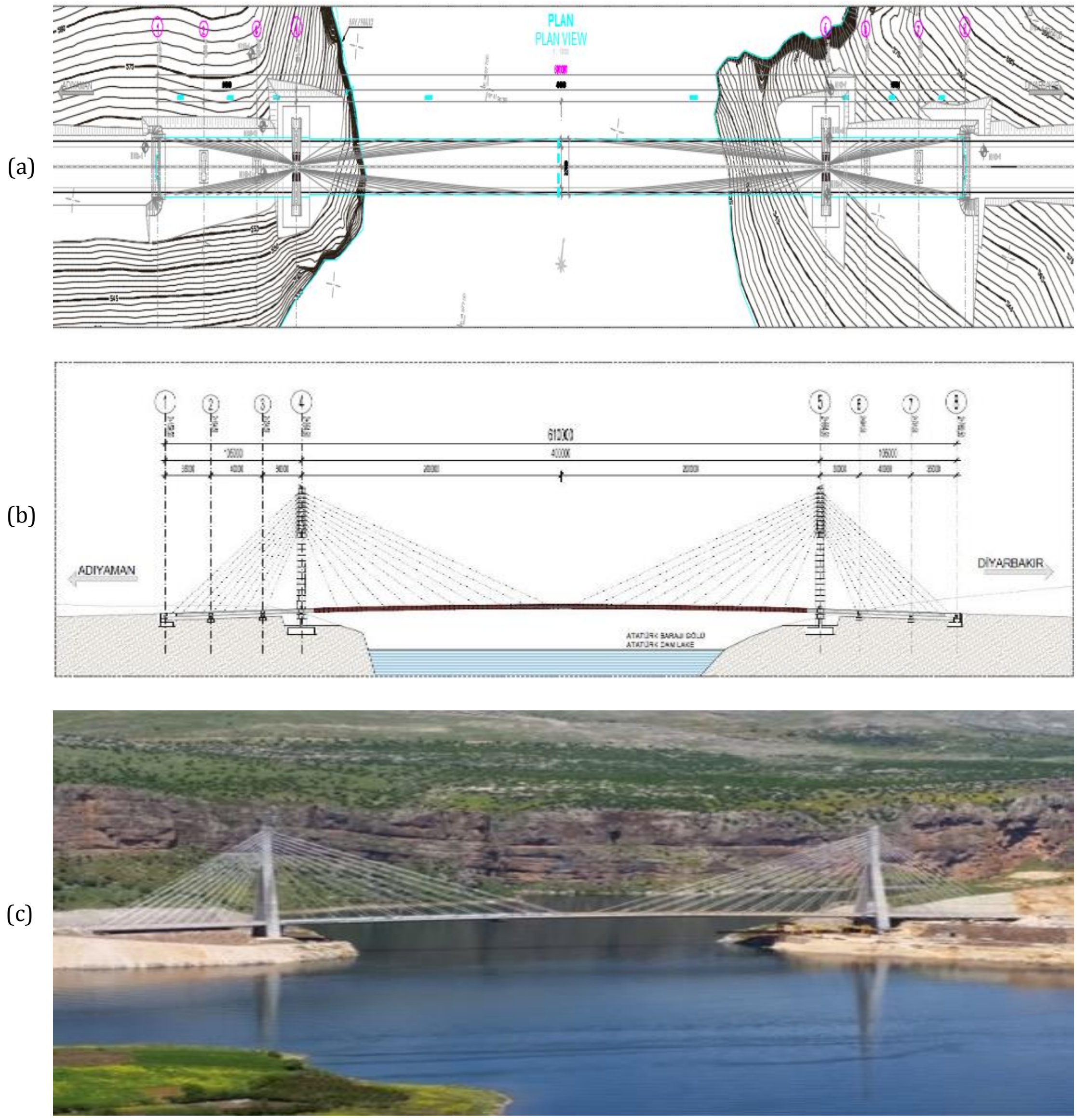
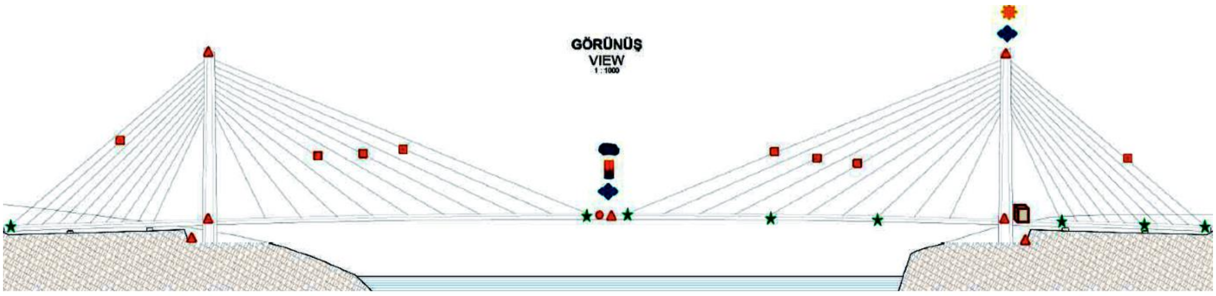


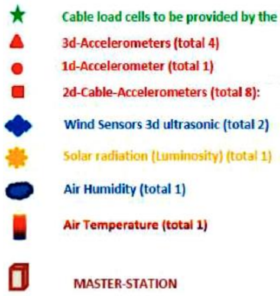
Fig. 1. (a) Plan; (b) longitudinal section; and (c) view from Nissibi Bridge (NBP, 2012; NBR, 2015).

3. Structural Behaviors of Main Structural Elements under Environmental Effects

The cables, pylons and deck behaviors under environmental effects such as air temperature, humidity and wind speed are investigated in this section. The forces and acceleration responses of bridge elements measured from the bridge monitoring system are compared for various environmental meteorology. The data recorded in the hottest summer (July 31, 2015) and the coldest winter (January 1, 2016) days are chosen for the comparisons. The daily variations of air temperature, humidity and wind speed with time are shown in Fig. 4. It can be seen from Fig. 4a that air temperature is above 30°C on July 31 and below 3°C on January 1. The temperature slightly decreases and reaches the minimum in the early morning in both day. The temperature then increases to the maximum in the early afternoon and decreases in the evening and at midnight. The temperature reaches a minimum of approximately 0°C at around 05:00 hrs on January 1 and a maximum of approximately 36°C at around 16:00 hrs on July 31. The relative humidity ratio on January 1 is higher than the ratio on July 31. The humidity decreases and reaches minimum in the evening in both days. Maximum wind speed is observed over 12 m/s on January 1, whereas the maximum wind speeds occur in the afternoon on July 1 and at midnight on January 31. In general, the change in temperature between

July 31 and January 1 is the most significant among all environmental effects measured. The variation of the cables, pylons and deck responses of the bridge due to the above explained environmental effects are discussed below. It is noted that the monitoring data for these elements include the combination of the dead and traffic loads and environmental effects. The traffic-induced component could not be separated from the data.





Pos.	Sensorgroup	Abbr.	Nos. of Sensors	Nos. of Channels
1	Ultrasonic wind 3D	UW	2	6
2	Air Temperature/Humidity	AT_H	1	2
3	Solar Radiation	SOL	1	1
4	Accelerometer 3D	A3	7	21
5	Accelerometer 1D	A1	1	1
6	Cable Accelerometer 2D	CA	8	16
7	Transmitter for Cable Load Cell	T-LC	8	8

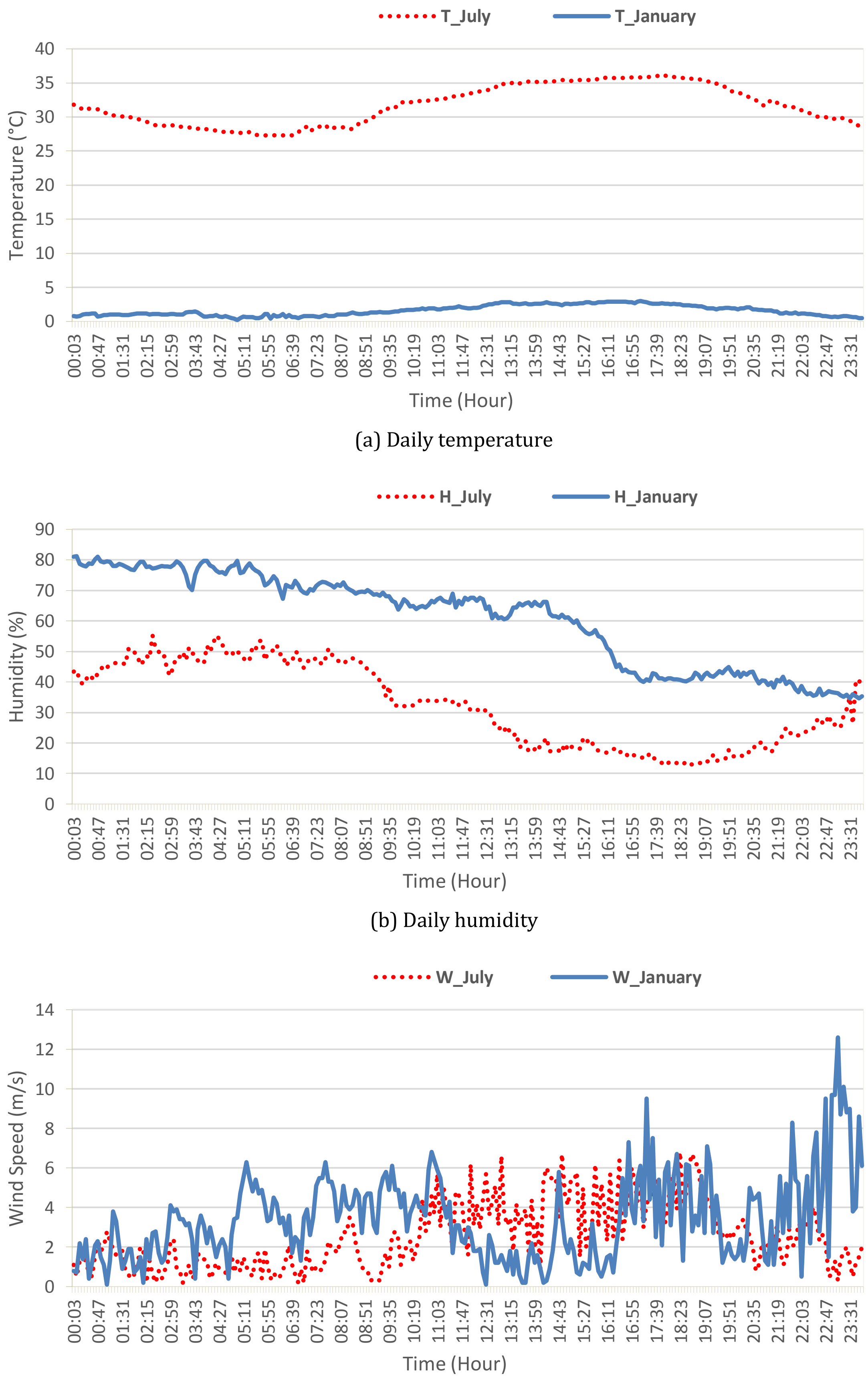
Fig. 2. The sensor types and locations in Nissibi Bridge (VCE, 2012).

Fig. 3. Some views from sensors located in Nissibi Bridge (NBR, 2015).

3.1. Environmental effects on cable behaviors

The properties of cables on the pylons P4 and P5 are shown in Fig. 5. The prestressed concrete and steel deck are carried by 20 double cables (80 cables in total) in the left and right of pylons P4 and P5. Cables 160, 260, 360 and 451 are selected for the investigation of the response of the cable forces under temperature and wind effects.

It can be seen from Fig. 5 that Cables 160 is with length of 130m, 55 strands and 200mm diameter; and Cable 260 and 360 is with length of 205m and 50 strands and 200mm diameter. Both cables have dampers and are in the right side of the deck. Cable 160 is in the Adıyaman side of pylon P4. Cable 260 at pylon P4 and Cable 360 at pylon P5 are in the middle of the deck span. Cable 451 is with length of 63m, 37 strands and 180mm diameter and is in the Adıyaman side of pylon P5. The environmental effects on cable forces are investigated for an individual strand force in each cable.



(a) Daily temperature

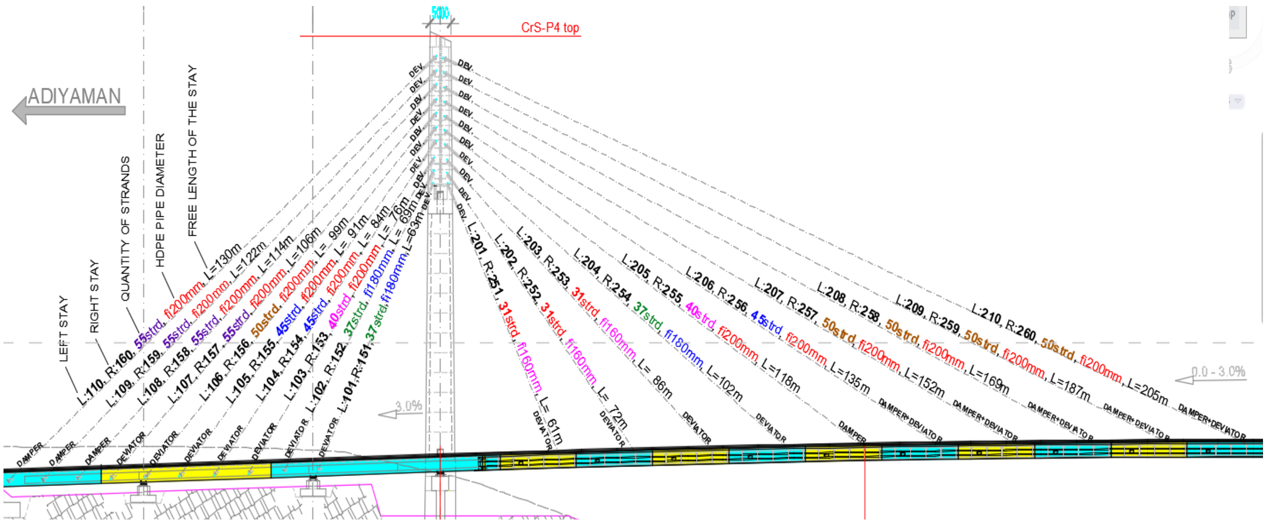
H_July
H_January
Humidity (%)
Time (Hour)

(b) Daily humidity

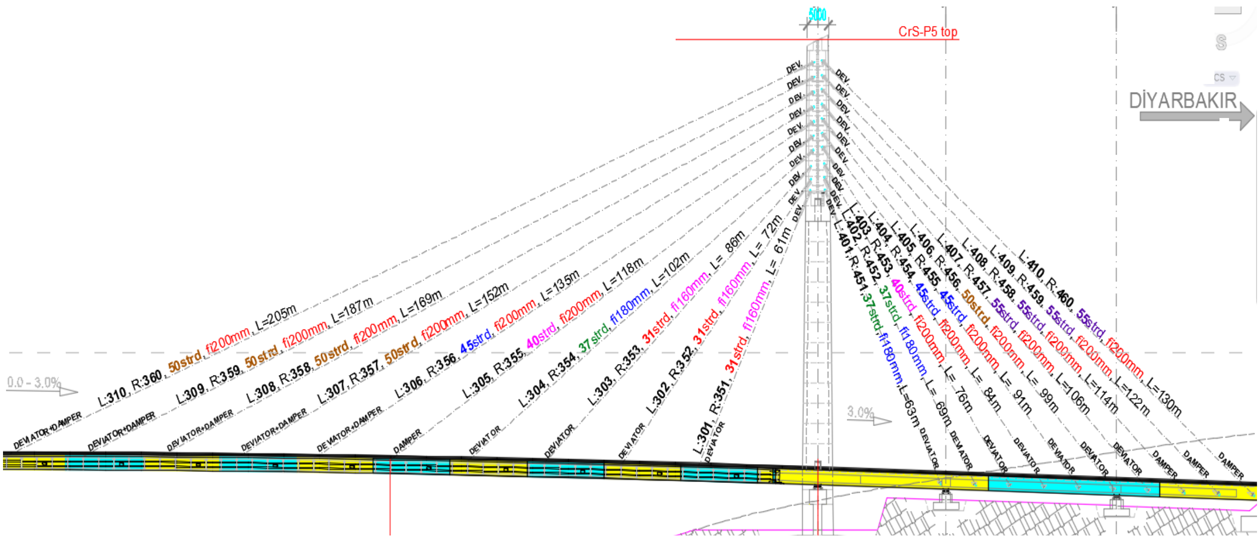
W_July
W_January
Wind Speed (m/s)
Time (Hour)

(c) Daily wind speed

Fig. 4. Variations of air temperature, humidity and wind speed on July 31, 2015 and January 1, 2016.



(a) Pylon P4



(b) Pylon P5

Fig. 5. Cable properties on the pylons P4 and P5 (NBP, 2012; NBR, 2015).

3.1.1. Temperature effects on cable forces

The variations of temperature and humidity in January 1 and July 31 are shown in Figs. 4a and 4b. The variation of cable forces with air temperature on July 31 and January 1 are depicted for cables 160, 260, 360 and 451 in Figs. 6 and 7. It can be seen from Figs. 6 and 7 that the values of cable forces slightly change in July 31 and January 1 throughout the day. The cable forces increase and reaches the maximum values in the early morning on January 1, in which temperature has smallest values. Besides cable 160, cables forces recorded in July 31 have maximum values in the afternoon, in which temperature has maximum values.

The cable forces in Adıyaman and Diyarbakır sides at pylon P4 and P5, respectively, have different values as shown in Figs. 6 and 7. When compared the forces for cable 260 at pylon P4 and Cable 360 at pylon P5, which has the same length and section properties, the forces recorded for Cable 360 at pylon P5 are larger than those of Cable 260 in January 1 and July 31. However, similar results cannot be obtained for Cable 160 at pylon P4 and Cable 451 at pylon P5.

Comparison of cable forces for Cables 160, 260, 360 and 451 in July and January are shown in Fig. 8. It can be seen from Fig. 8 that while the forces of Cables 160 at pylon P4 and 451 at pylon 5 carrying prestressed concrete deck show approximately constant variation, the forces of Cables 260 and 360 carrying steel deck show more variation through day. Temperature difference between July 31 and January 1 is about 30^{0}C (Fig. 4a). It can be generally stated that the daily temperature differences in the hottest summer and the coldest winter days changes the cable forces by up to 10%.

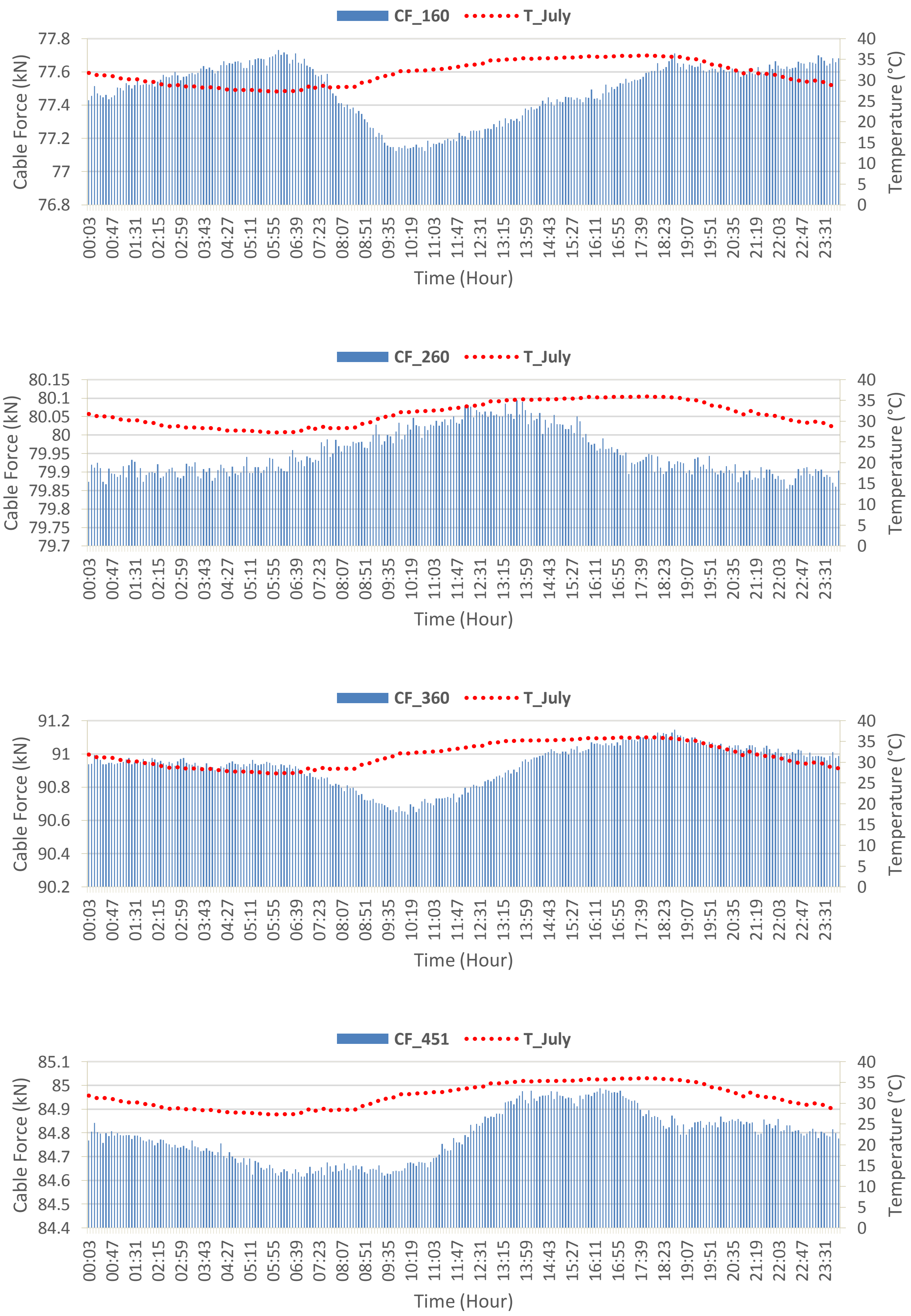


Fig. 6. The variation of cable forces with air temperature on July 31 for cables 160, 260, 360 and 451.

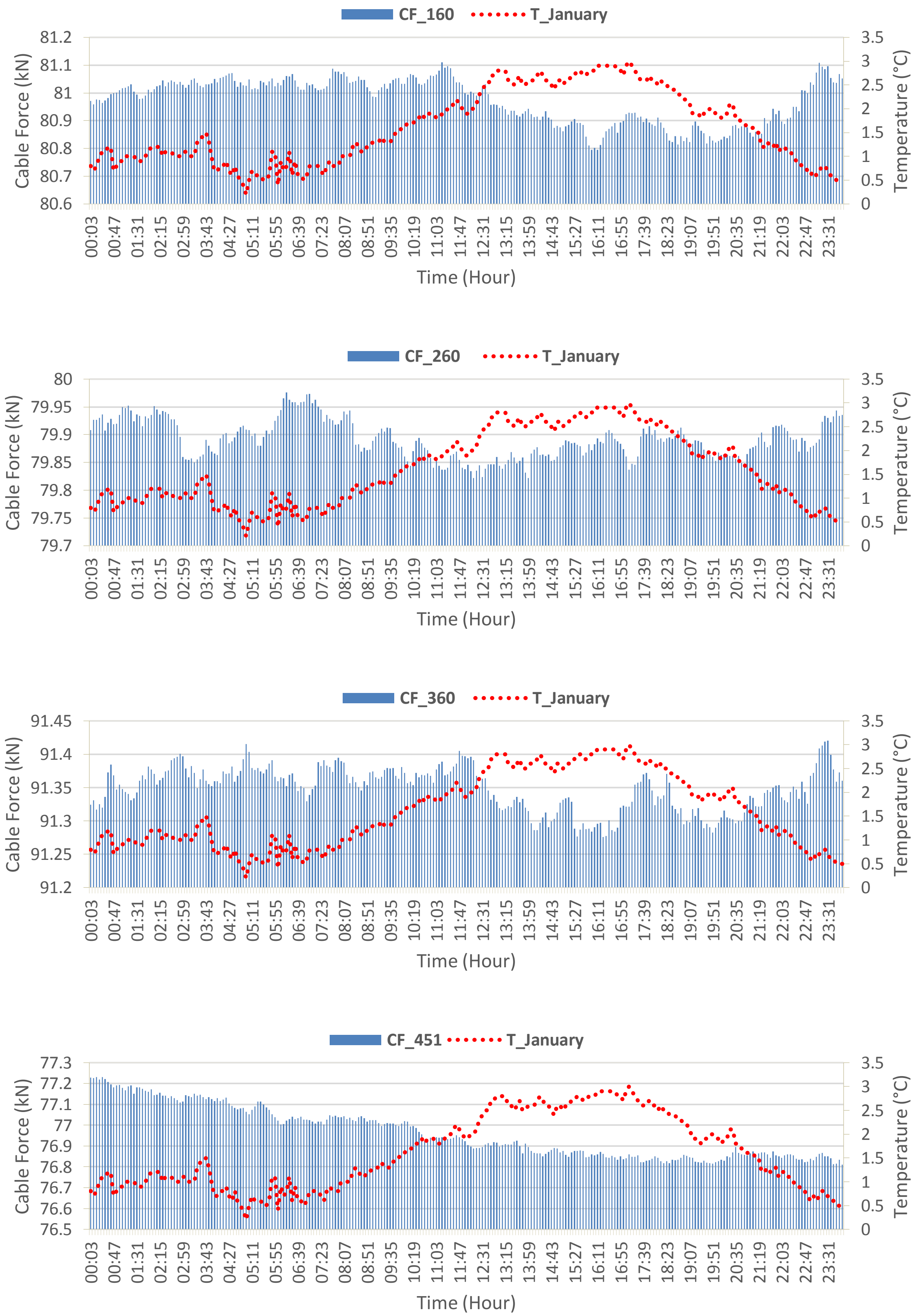


Fig. 7. The variation of cable forces with air temperature on January 1 for cables 160, 260, 360 and 451.

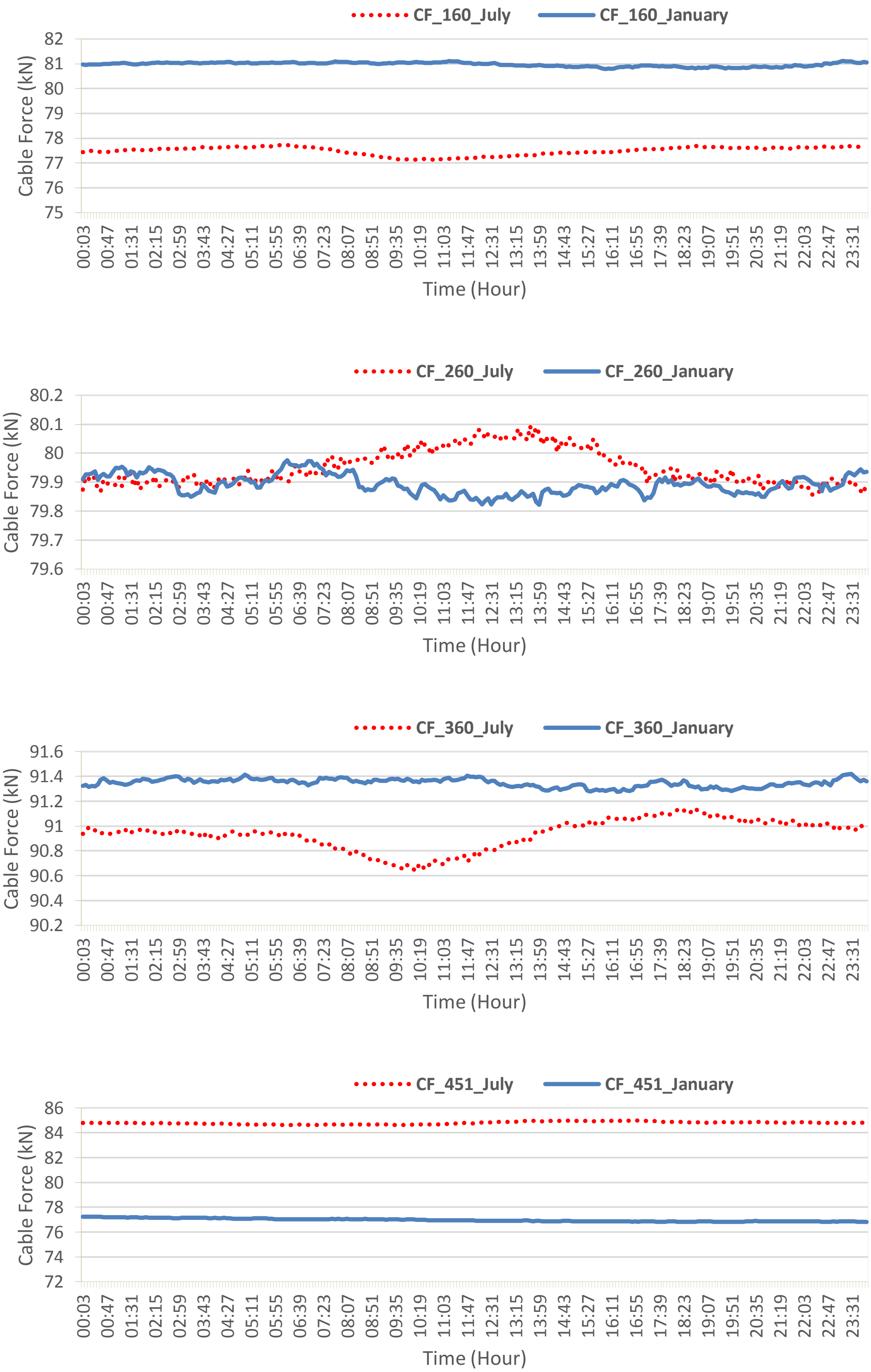


Fig. 8. Comparison of cable forces for 160, 260, 360 and 451 on July 31 and January 1.

3.1.2. Wind speed effects on cable forces

The design wind speed was taken into account as 33.6m/s (120km/h) at the design stage of the bridge. Variations of wind speed on July 31 and January 1 are shown in Fig. 4c. Maximum wind speed recorded was slightly over 12m/s in January 1. The variation of forces for Cable 160, 260, 360 and 451 on July 31 and January 1 are shown in Figs. 9 and 10. It is seen from the figures that wind speeds are more effective on January 1. The cable forces increase with increasing wind speed in the afternoon in July 31 and at the midnight on January 1. It can be generally stated that the daily wind speeds in the hottest summer and the coldest winter days affect the cable forces slightly.

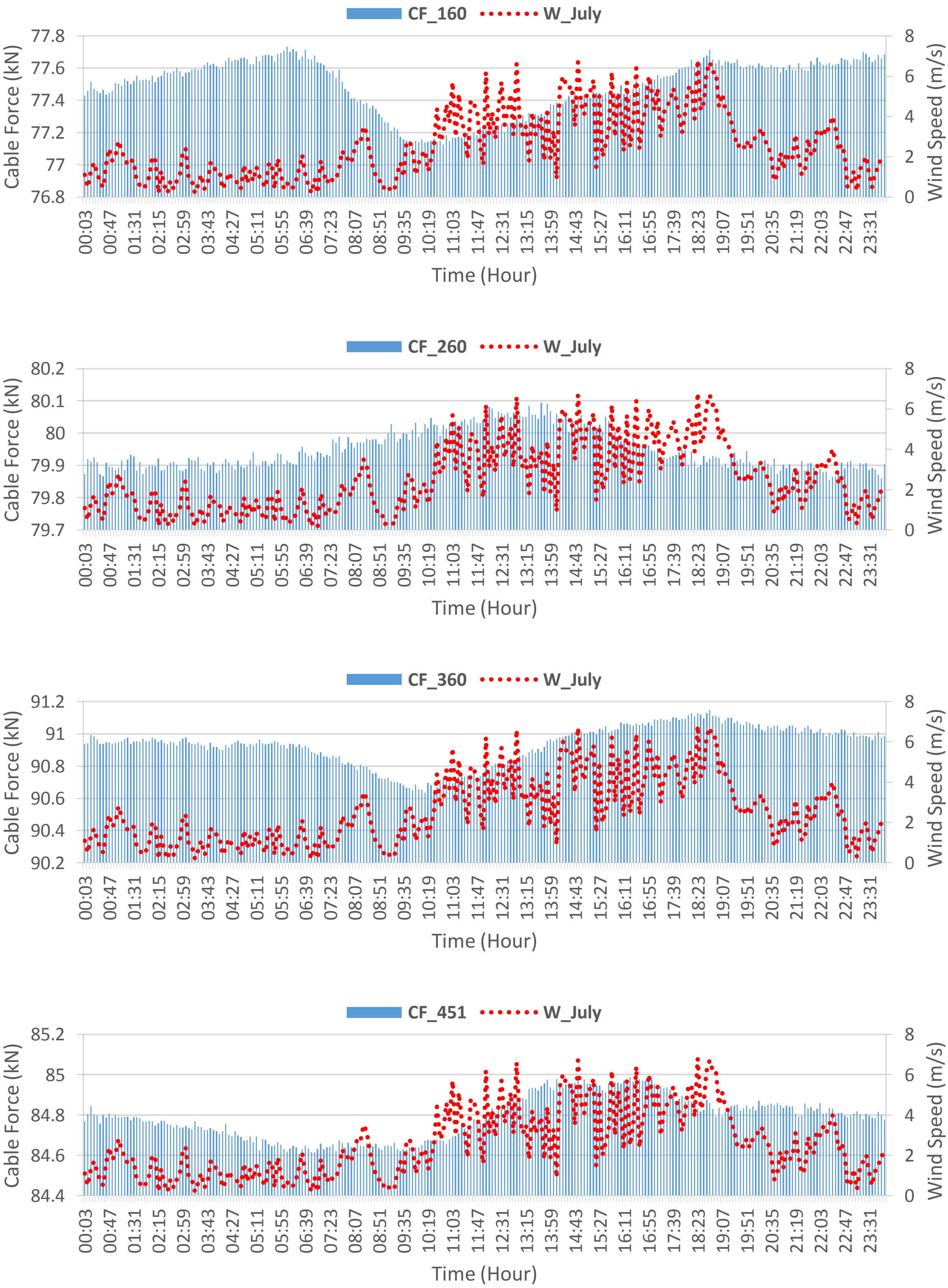


Fig. 9. The variation of cable forces with wind speed on July 31 for cables 160, 260, 360and 451.

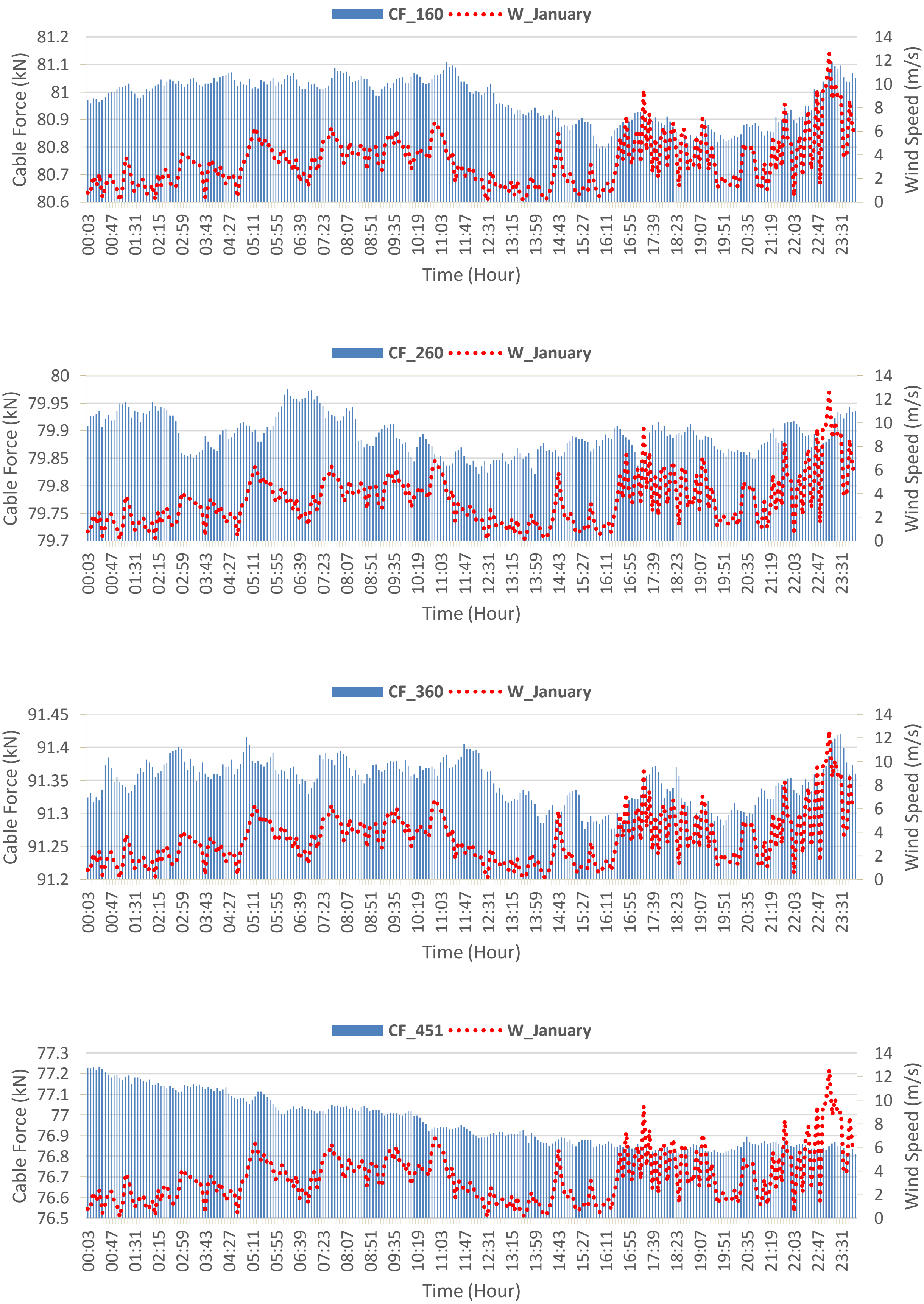


Fig. 10. The variation of cable forces with wind speed on January 1 for 160, 260, 360 and 451.

3.1.3. Environmental effects on cable accelerations

Cables 159 and 259 at pylon 4 are selected to investigate the environmental effects on cable accelerations. The variations of accelerations recorded on Cable 159 and 259 in transverse (1) longitudinal (2) directions of the cables on July 31 and January 1 are given in Fig. 11.

The accelerations in longitudinal (2) direction are smaller than those of the transverse (1) direction. Besides the accelerations in 1 (transverse) direction in Cable 259, all cable accelerations change slightly along the day of January 1. However, accelerations recorded in July 31 show increasing and decreasing changes throughout the day.

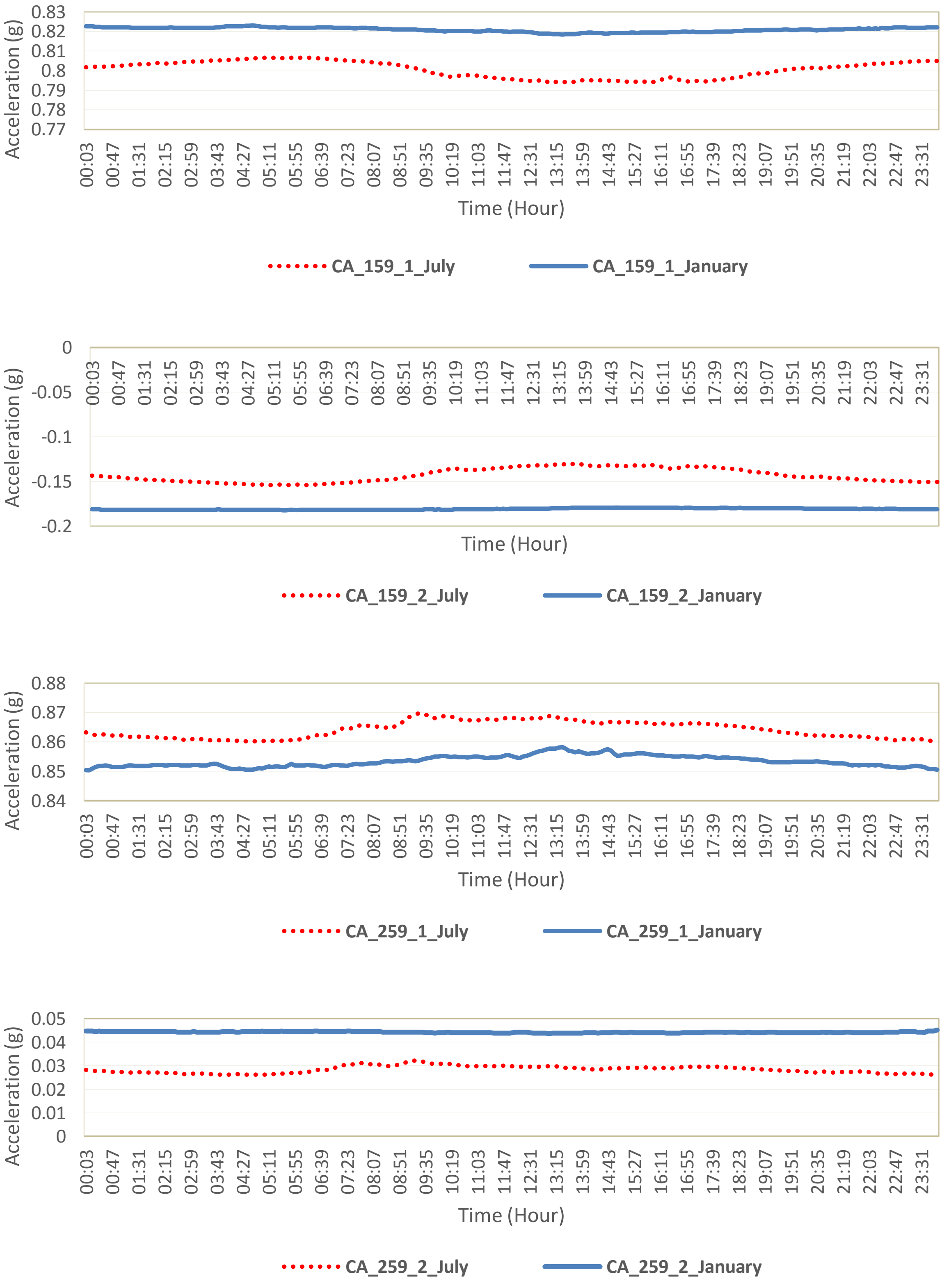


Fig. 11. Comparison of cable accelerations in transverse (1) and longitudinal (2) directions for 159 and 259 on July 31 and January 1.

3.2. Environmental effects on pylon behaviors

Bridge has two pylons named P4 and P5. P4 is in Adıyaman side and P5 is in the Diyarbakır side (Fig. 5). The accelerometers mounted on the top levels of the pylons are shown in Fig. 12. Each accelerometer can take data in three directions such as longitudinal (x), transverse (y) and vertical (z).

The acceleration components recorded on the top of pylons P4 and P5 in July 31 and January 1 are depicted in Figs. 13 and 14. It can be seen from Figs. 13 and 14 that the biggest accelerations occurred in the vertical (z) direction in both July 1 and January 31. The pylon accelerations in Adıyaman and Diyarbakır sides at pylon P4 and P5, respectively, have different values. The acceleration values recorded at the top of pylon P5 are higher than those of the pylon P4. Although accelerations show almost constant variation in January 1, they behave changeable in July 31 in pylon P4 and P5. The values of accelerations in July 31 generally decrease towards noon and increase towards night.

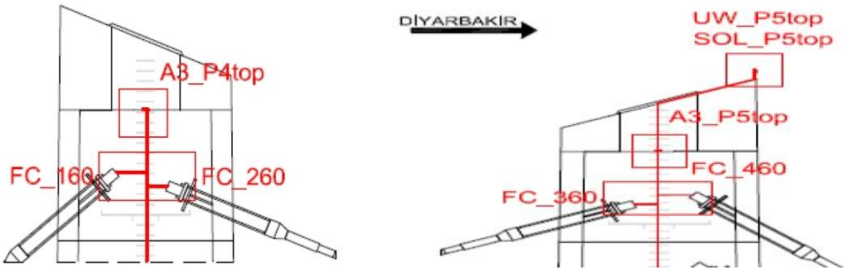


Fig. 12. Accelerometer locations on the P4 and P5 pylons (NBP, 2012; NBR, 2015).

Fig. 13. Comparison of accelerations recorded on the top of pylon P4 in longitudinal (x), transverse (y) and vertical (z) directions on July 31 and January 1.

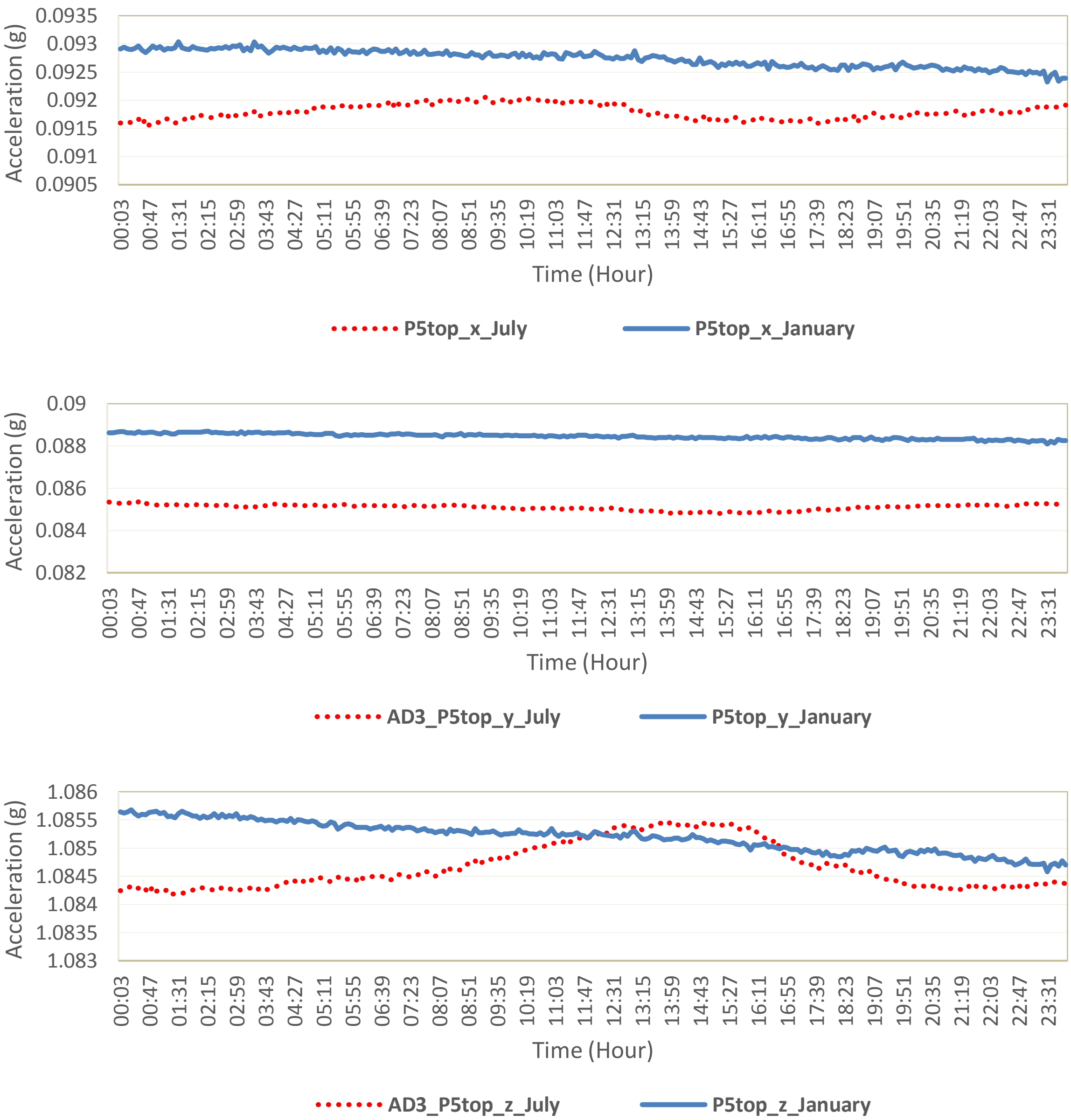


Fig. 13. Comparison of accelerations recorded on the top of pylon P5 in longitudinal (x), transverse (y) and vertical (z) directions on July 31 and January 1.

3.3. Environmental effects on deck behavior

The accelerometer mounted on the deck center is given in Fig. 15. The accelerations recorded on the deck center in longitudinal (x), transverse (y) and vertical (z) directions are plotted in Fig. 16. The largest acceleration occurred in the vertical (z) direction in both July 31 and January 1. While accelerations in January 1 show almost constant variation, the accelerations in July 31 increase towards to noon and decrease to the night.

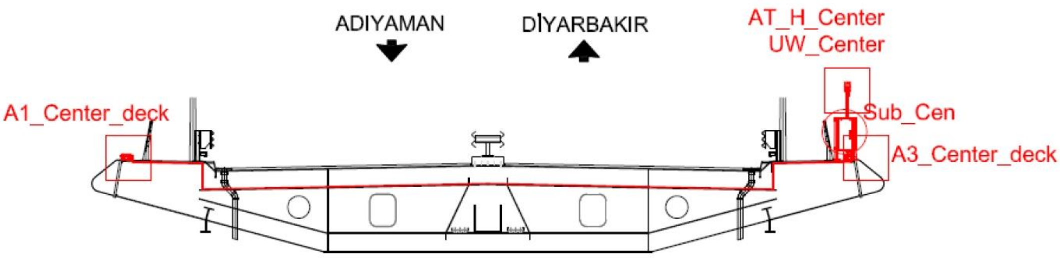


Fig. 14. Accelerometer locations at the deck center (NBP, 2012; NBR, 2015).

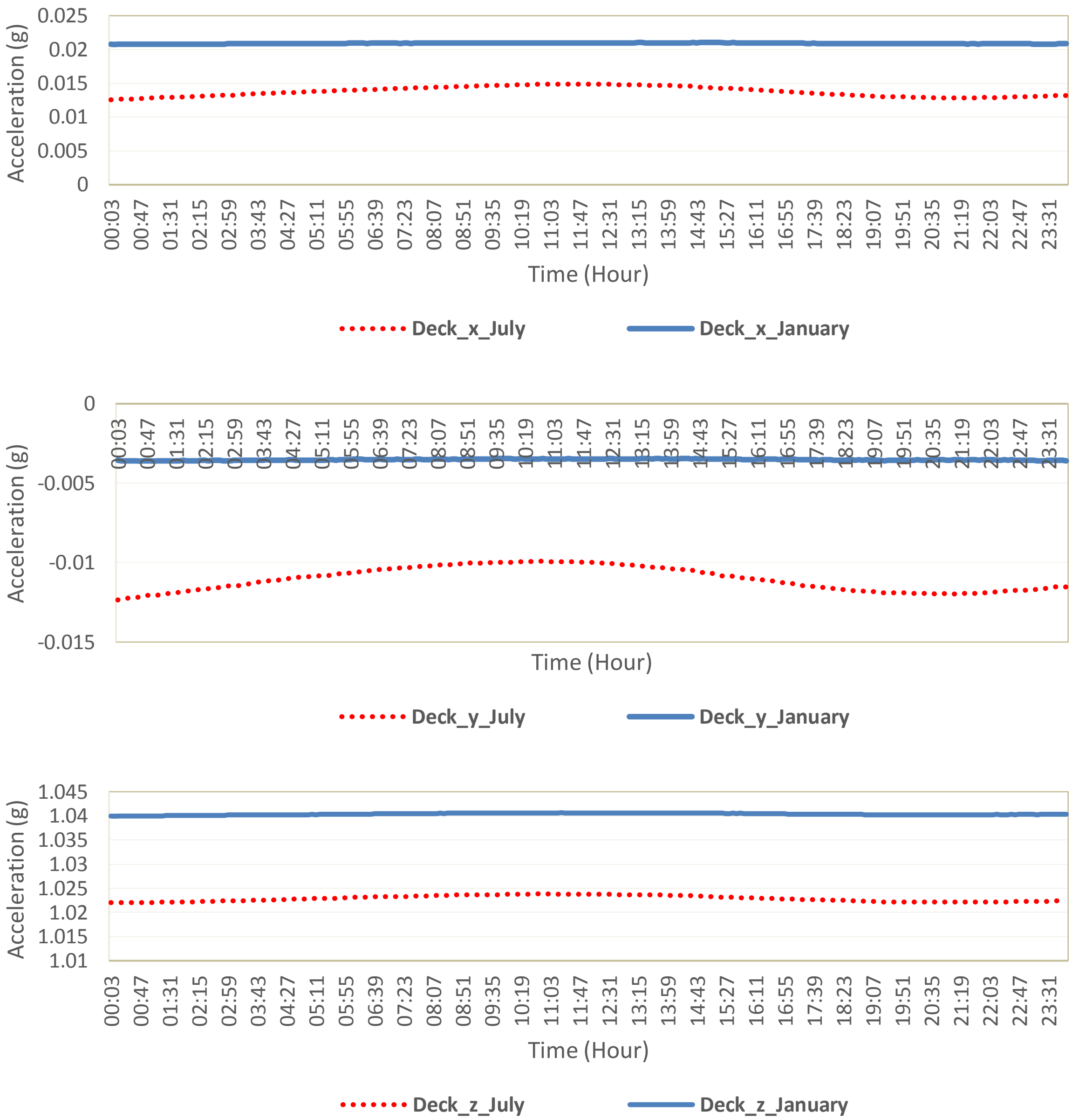


Fig. 16. Comparison of accelerations recorded on the deck center in longitudinal (x), transverse (y) and vertical (z) directions on July 31 and January 1.

4. Conclusions

The monitored structural behavior of cables, pylons and deck of a long span cable-stayed bridge are investigated under environmental effects such as air temperature and wind speed. The daily variations of cable forces and accelerations, and pylon and deck accelerations are obtained for the hottest summer (July 31, 2015) and the coldest winter (January 1, 2016) days. The results obtained from the study are summarized below as:

- The values of cable forces changes depending the daily air temperature. The cable forces increased and reached the maximum values in the early morning of January 1, in which temperature has the lowest values. Cables forces recorded on July 31 generally have maximum values in the afternoon, in which temperature has also the maximum values.
- The wind speed has more effect on the cable forces on January 1. The forces of the long cables increase with increasing wind speed in the afternoon for both July 31 and January 1.
- The cable accelerations in longitudinal direction are smaller than those of the transverse direction. While the cable accelerations recorded on July 31 show an increasing and decreasing changes, they change slightly in January 1 throughout the day.
- The pylon accelerations in Adıyaman and Diyarbakır sides at pylon P4 and P5, respectively, have different values. The values of the acceleration recorded in pylon P5 are higher than those of pylon P4. Although accelerations show almost constant variation in January 1, they exhibited more variation in July 31. The values of accelerations in July 31 generally decrease towards noon and increase towards night.

- While accelerations recorded in the deck center in January 1 show almost little variation, the accelerations in July 31 increase towards noon and decrease towards the night.
- The maximum accelerations in the deck and pylons occur in vertical directions. The cable accelerations in longitudinal direction are smaller than those of the transverse direction.

It is generally stated from the results that the structural behaviors of cable-stayed bridges are sensitive to the changing environmental load distributions due to their highly statically indeterminacy. Therefore, special attention must be given during the data taken from the bridge monitoring system and evaluated by experienced engineers.

Acknowledgements

The authors would like to express sincere thanks to General Directorate of Highways, the 9th Regional Directorate of Highways, GÜLSAN Inc. and EMAY Inc. for their contributions.

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