ENVIRONMENTAL INFLUENCES ON BRIDGES: AN ASSESSMENT STUDY

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Environmental conditions resulting from climate change may have diverse impacts on the safety and performance of infrastructure. Bridges, as pivotal structural components of transportation systems, are subject to various natural and environmental factors. Therefore, periodic definition of their dynamic characteristics, such as natural frequencies through experimental measurements, is crucial for promptly and accurately assessing their current state. In this study, experimental analysis is employed for this purpose, involving the measurement of structural responses under ambient conditions. This paper presents an investigation into the environmental effects on the dynamic characteristics of reinforced concrete (RC) frame bridges. The study focuses on two overpasses with similar geometries. Three sets of measurements were conducted for each overpass: in October 2017, March 2020, and May 2022. The identified dynamic characteristics were compared across different time points and correlated with environmental effects. The analysis results indicate that the identified natural frequencies effectively reflect changes in the dynamic characteristics of the overpasses due to environmental effects. A significant difference in identified natural frequencies is observed in the longitudinal direction, while minimal variation occurs in the vertical direction.

Keywords: ambient vibration measurements, dynamic characteristics, reinforced concrete bridges, condition assessment

1. INTRODUCTION

Bridges are inevitably exposed on the daily, seasonal, and annual air temperature variations which affects the characteristics of the structures. During their service life, local damage can be reflected by the changes in dynamic properties. Therefore, a successful damage assessment relies heavily on the prediction accuracy of the dynamic properties. The variations of modal parameters caused by environmental factors are very significant and often greater than those caused by structural damage [1] or normal loads [2]. The periodic (diurnal, seasonal, and yearly) and transient temperature variations always mask changes in dynamic properties due to actual damage. Recently, more research has focused on the effect of temperature on the dynamic properties of bridges [3].

In practice, the effect of temperature variations on structural dynamic properties have been attributed to the reasons outlined below. First, structural deformations occurred with variations in temperature-varying environments and were called large deformation effects [4]. Second, structural stiffness changed because of thermal stress in the well-known stress stiffening effect [5]. In addition, material properties were temperature dependent; for example, the decrease in the elastic modulus of concrete and of steel led to a reduction in modal frequencies. Furthermore, and equally important, the elastic properties of support (especially for bridge structures) were more easily affected by thermal variations, and at low temperature, the boundary conditions also changed suddenly [6]. Accordingly, the factors that affected the dynamic properties of bridge structures were complex and led to some specific damage detection methods, such as technology that does not need estimations of the modal parameters [7]. In addition, a thermal performance study of bridges based on long-term monitoring data still piqued researcher interest [8]; however, the cost of the health monitoring system was high, despite increasingly more advanced structural health monitoring (SHM) technologies [9]. To remove the environmental impacts, regression-based analysis [10] and principal component analysis [11] were adopted, but these analyses were data-driven black box modeling techniques. Although Zhou and Song [12] proposed a physics-based environmental-effects-embedded model updating method to overcome these shortcomings, the selection of the updating parameters was also critical, and a large deflection effect was not taken in account.

In the present study, time-varying thermodynamic properties of 2 span girder bridges were analyzed and compared.

2. RESEARCH METHOD

2.1 MEASURING EQUIMPMENT

The dynamic characteristics have been determined by measurements of ambient vibrations. The equipment with an acquisition system that was used to take the measurements, is sensitive accelerometers that have recorded the records. In this case PCB Piezotronics devices, model 393B12, manufactured by National Instruments with a sensitivity of 10,000 mV and a range of up to 4.9 m/sec^2, with a size of 0.5g were used. Data acquisition was performed with the acquisition system - module NI cDAQ-9178 and 4 NI 9234 boards (Fig. 1). The recorded acceleration measurements are expressed in "Earth acceleration - g" (9.81 m/sec^2).

Figure 1. Field monitoring equipment (left), three-way accelerometer (right)

The measurements were carried out using a sampling rate of 2.048 Hz. In total, 15 accelerometers were used with various measurement locations and directions. During the measurements, the sensors were placed in the different points of the bridge: in the middle of the bays and above the piers. During all measurements, one accelerometer was located in a reference point in order to enable the comparison of the amplitudes of the other sensors with the reference points for defining the tonal forms of vibration. These measurements cover a frequency range from 0 to 40 Hz, where the first resonant frequencies are found. The processing of the record was carried out by applying a fast Fourier transformation so that it was possible to define the frequency composition of the registered vibration from which the natural frequencies of the objects could be identified.

2.2 MEASURING PROCEDURE

Withing the framework of this research, field measurements of two overpasses (OP2 and OP3, Fig. 2) were carried out. The selected bridges are located over the "Friendship" highway, Demir Kapija - Gevgelija section, designed according to modern regulations that consider the seismic action. Both overpasses are with 2 spans each of which 23 m. The selected bridges are designed according to modern regulations that consider the seismic action. The initial measurements of the structures were carried out in October 2017, during which the trial loading of the bridges with static and dynamic loads was performed.

Figure 2. Measured structures OP2 and OP3

The load capacity and deformability of the built construction is compared with the results of the design project. The precision of the performance and the geometry of the elements were checked, and the quality of the incorporated materials and thus the usability of the construction was checked. At the beginning of March 2020, additional measurements were performed on the bridges with a duration of 10 min. The same measurements were repeated in May 2022. The two bridges were still not into use. Therefore, only the environmental conditions are the external factors that may effect the dynamic properties of the bridges. For performing the measurements, 15 accelerometers were used, in 5 places, 3 each in the longitudinal x direction, the transverse y direction and the vertical z direction, and they were placed on the edge of the upper structure, in the field and above the middle support (Fig. 3). During the first measurement, the accelerometers were placed on the part of the upper construction, in the direction of Skopje, while during the second measurement, they were placed in the direction of Gevgelija, with the first accelerometer as a benchmark during both measurements being placed in the same place.

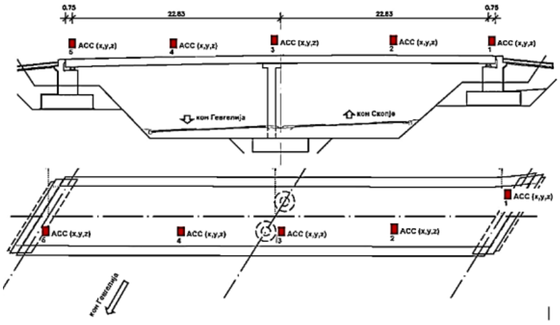

Figure 3. Position of accelerometers on the measured bridge at base and cross-section

2.2.1 Modal damping estimation methods

The methods available to perform identification of modal parameters (in this case modal damping, but it is the same for all modal parameters) of dynamic systems based on their response to ambient excitation are classified as frequency domain or time domain methods. The frequency domain methods start from the output spectrum of half- spectrum matrices estimated from the measured outputs. After obtaining the frequency response curves of the analysed system, modal damping can be measured using half-power bandwidth method and Enhanced Frequency Domain Decompositon (EFDD) method. The half-power bandwidth method consists of locating the resonant frequency and two nearby frequencies f1 and f2 located in the frequency spectrum by application of equation 1:

$$\xi = \frac{f_2 - f_1}{2f_r} \times 100\% \qquad (1)$$

Enhanced Frequency Domain Decompositon was performed in order to calculate the damping (IRF) by using the impulse response of a single degree of freedom. Once a set of points with similar singular vectors is selected for a particular mode (Fig. 4a), this segment of an auto-spectrum may be converted to a time domain (Fig. 4b).

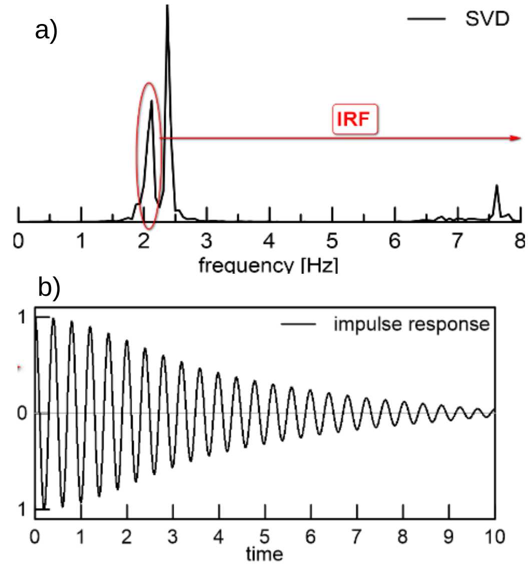

Figure 4. FDD method, estimation of the modal damping ratio

An auto-correlation function with the contribution of a single mode is obtained. As the output correlation of a dynamic system excited by white noise is proportional to its impulse response, it is possible to estimate the modal damping coefficient. This can simply be performed by fitting an exponential function to the relative maxima of the correlation function and extracting the modal damping ratios from the parameters of the fitted expression taking into account the classical expression for the impulse response of a single degree of freedom.

2.2.2 OP2 Results

Using the previously described procedure, most of the records were obtained at individual points of the investigated bridge. Based on these registrations and their singular value of spectral densities, a certain amount of data on the dynamic characteristics of the investigated structures were obtained. Below, on Fig.5 the curves of singular value of spectral densities for OP2 are presented.

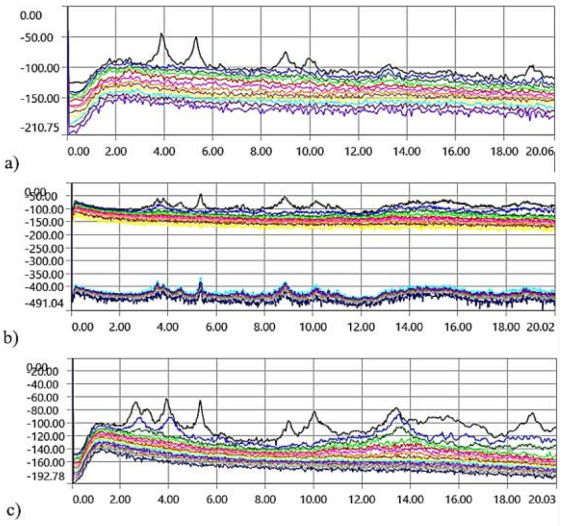

Figure 5. Singular value of spectral densities for OP2 a) 2017, b) 2020, c) 2022

Table 1 shows the frequencies obtained from all measurements, when the accelerometers were placed on the part of the upper construction in the direction of Skopje (measurement 1). From the obtained results, it can be concluded that almost all accelerometers that measured the acceleration in a certain direction show similar results, that is, for longitudinal direction, the frequency is 2.58Hz for 2017year, 3.58 for 2020year and 2.65Hz for 2022.

Table 1 Natural frequencies of the structure for OP2

Mode	Direction	Frequency [Hz]		
		2017	2020	2022
1	Longitudinal	2.58	3.58	2.65
2	Transversal	2.97	3.80	3.12
3	Vertical	3.88	3.81	3.91

It can be seen that the frequency has increased in 2020 and in 2022 came back. In the Transversal direction, the frequency of the structure is 2.97Hz for 2017year, 3.80 for 2020 and 3.12Hz for 2022. In the vertical direction, the frequency of the structure is 3.88Hz for 2017, 3.81 for 2020 and 3.91Hz for 2022. In this direction, the frequency decreased in 2020 and then in 2022 increased to 3.91Hz.

Table 2 shows the damping for each frequency by two methods: half power and IRF. In general, the damping calculated by the two methods corelates with each other. For the first frequency in the vertical direction, the damping is within the range of 0.88% for 2017, 0.73% for 2020 and 1.25% for 2022. For the first frequency in the longitudinal direction, the damping is within the range of 0.71% for 2020 and 3.3% for 2022.

Table 2. Modal damping [%] for OP2

No.	2017			2020			2022		
	Freq.	Half Power	IRF	Freq.	Half Power	IRF	Freq.	Half Power	IRF
1 (V)	3.88	0.80	0.88	3.81	0.37	0.73	3.91	0.73	1.25
2 (V)	5.31	0.58	0.64	5.40	0.39	0.46	5.32	0.40	0.45
3 (L)	2.58	n/a	n/a	3.58	0.54	0.71	2.65	2.43	3.3

V (vertical)
L (Longitudinal)

Fig. 6 presents in more clear way, the difference between the modal damping for OP2 calculated in 2017, 2020 and 2022 according to half power and IRF methods.

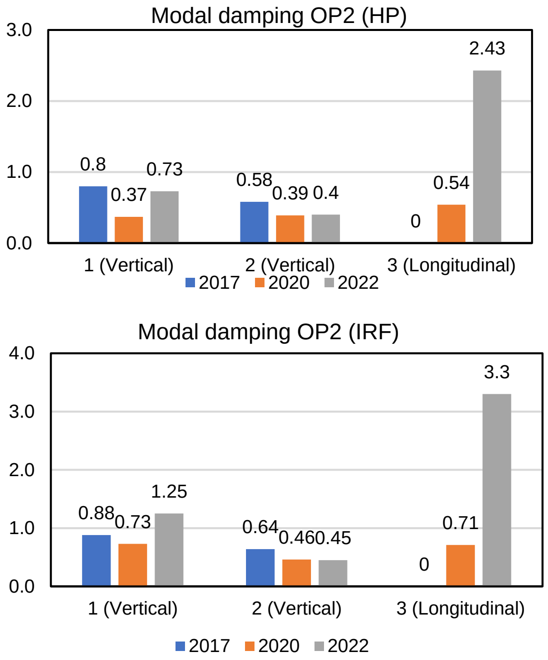

Figure 6 Modal damping [%] for OP2

2.2.3 OP3 Results

Using the same procedure za OP2, all records were obtained at individual points of the investigated bridge. Based on these registrations and their singular value of spectral densities, a certain amount of data on the dynamic characteristics of the investigated structures were obtained. Below, on Fig. 7 the curves of singular value of spectral densities for OP3 are presented.

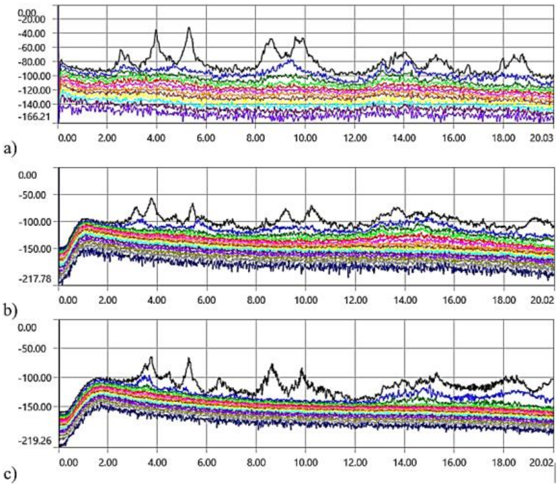

Figure 7. Singular value of spectral densities for OP3 a) 2017, b) 2020, c) 2022

Table 3 shows the frequencies obtained from all measurements, when the accelerometers were placed on the part of the upper construction in the direction of Skopje (measurement 1) for bridge OP3. From the obtained results, it can be concluded that almost all accelerometers that measured the acceleration in a certain direction show small differences in natural frequencies. For longitudinal direction, the frequency is 2.53Hz for 2017 year, 3.14 for 2020 year and 3.50Hz for 2022. It can be seen that the frequency has continuously increased in 2020 and in 2022. In the Transversal direction, the frequency of the structure is 2.84Hz for 2017 year, 3.49 for 2020 year and 3.77Hz for 2022. In the vertical direction, the frequency of the structure is 3.98Hz for 2017 year, 3.78 for 2020 year and 3.78Hz for 2022. In this direction, the frequency decreased in 2020 and continued with same value till 2022.

Table 3. Natural frequencies of the structure for OP3

Mode	Direction	Frequency [Hz]		
		2017	2020	2022
1	Longitudinal	2.53	3.14	3.50
2	Transversal	2.84	3.49	3.77
3	Vertical	3.98	3.78	3.78

Table 4 shows the damping for each frequency by two methods: half power and IRF. In general, the damping calculated by the two methods corelates with each other. For the first frequency in the vertical direction, the damping is within the range of 0.78% for 2017, 1.44% for 2020 and 1.06% for 2022. For the first frequency in the longitudinal direction, the damping is within the range of 0.82% for 2017 and 2.18% for 2020.

Table 4. Modal damping [%] for OP3

No.	2017			2020			2022		
	Freq.	Half Power	IRF	Freq.	Half Power	IRF	Freq.	Half Power	IRF
1 (V)	3.98	0.59	0.78	3.78	1.15	1.44	3.78	1.06	1.06
2 (V)	5.28	0.61	0.84	5.35	0.49	0.65	5.27	0.25	0.62
3 (L)	2.58	0.69	0.82	3.14	2.02	2.18	3.50	n/a	n/a

V (vertical)
L (Longitudinal)

In more clear way, Fig. 8 presents the difference between the modal damping for OP3 calculated in 2017, 2020 and 2022 according half power and IRF methods.

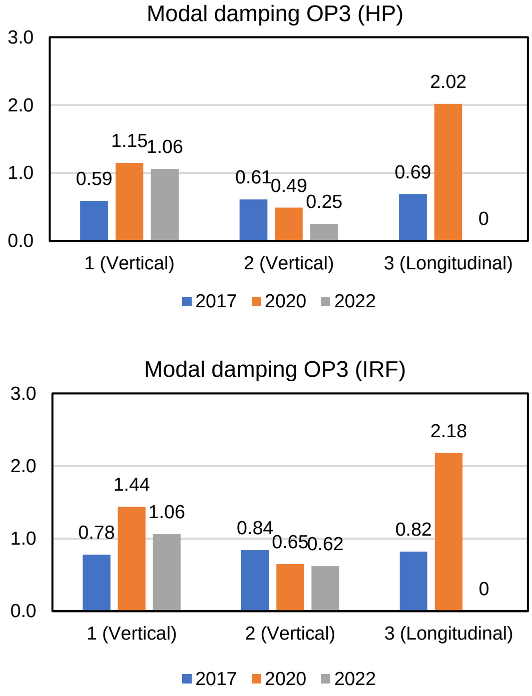

Figure 8 Modal damping [%] for OP3

3. WEATHER CONDITIONS

Engineering materials change their properties and are vulnerable to damage from the surrounding environment, whether they are concrete, steel, or wood. Some environmental factors are considered during structural design, primarily in terms of stress conditions. However, the changes in fundamental environmental conditions such as temperature and humidity can be challenging because they may influence structural dynamic properties. Environmental monitoring is therefore an essential component of this bridge measurement program. The monitoring program involves gathering information on temperature, humidity, and environmental data analysis. Because the object region has a limited number of monitoring sensors, a relatively good profile of the environmental conditions was constructed by collecting monitored data for at least 6 months before the bridge measurements. The weather monitoring was conducted for the years 2017, 2020 and 2022. The most essential information to consider in these records will be the extremes in averages of temperature and humidity.

3.1 TEMPERATURE

According to the monitored program, the regularly collected set of data was grouped into three monitoring periods. The first monitoring period was a period of one month before the bridge measurements, while the second monitoring period was a period of three months prior to the measurements. The last analyzed period was a period of six months before the structure's measurements. The determination of real temperature inside each structural part was not conducted because the measurements were only for ambient temperature. As a result, it was decided to evaluate how these conditions might affect the structural dynamic characteristics.

Table 5 Temperature observation for period of 1 month before bridge measurements

Year	Avg Max [^{O}]	Avg Mean [^{O}]	Avg Min [^{O}]	Max [^{O}]	Min [^{O}]
2017	23.7	15.7	8.3	37	-3
2020	13.3	6.5	0.3	25	-6
2022	23.1	15.2	7.5	34	-2

Table 6 Temperature observation for period of 3 months before bridge measurements

Year	Avg Max [^{O}]	Avg Mean [^{O}]	Avg Min [^{O}]	Max [^{O}]	Min [^{O}]
2017	28.6	20.5	12.3	40	-3
2020	10	4.5	-0.4	25	-9
2022	17.2	10.1	3.3	34	-9

Table 7 Temperature observation for period of 6 month before bridge measurements

Year	Avg Max [^{O}]	Avg Mean [^{O}]	Avg Min [^{O}]	Max [^{O}]	Min [^{O}]
2017	26.9	19.2	11.4	40	-3
2020	15.6	9.2	3.5	34	-9
2022	13.6	7.5	1.66	34	-10

Tables 5 to 7 show the ambient temperatures for 2017, 2020 and 2022. The temperature was studied for three periods of 1, 3 and 6 months before the measurements. For a period of 6 months, the average mean temperature for 2017 is 19.2°, while for 2020 and 2022 it has dropped to around 7.5-9.2°. For a period of 3 months, the average mean temperature is different for each year, where for 2017 it is 20.5°, for 2020 it is 4.5° and for 2022 it is 10.1°. For a period of 1 month, the average mean temperature for 2017 and 2022 is around 15.5°, while for 2020 it has dropped to 6.5°.

Fig. 9 show the temperature observation over past six months before bridge measurements: maximum daily values, minimal daily values, and average daily data.

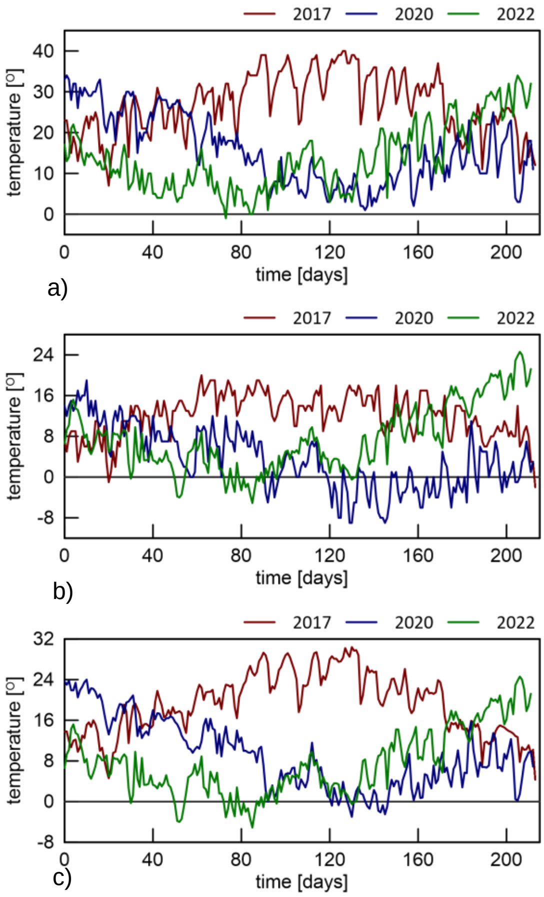

Figure. 9 Temperature observation over past six months before bridge measurements
a) Maximal daily values b) Minimal daily values c) Average daily data

Fig. 10 shows the maximum (red line), minimum (blue line) and average temperatures (grey) in ◦C, of the location in the period of the construction of the bridges to the end of the May, 2022, when the last measurements of the bridges were performed. Fig. 10 b) presents the temperature the air needs to be cooled to (at constant pressure) to achieve a relative humidity (RH) of 100% (source: www.wunderground.com).

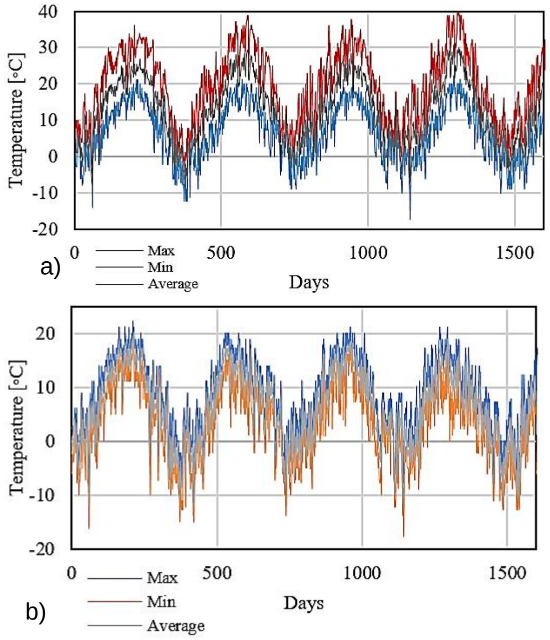

Figure 10. Maximum, minimum and average temperatures on the location, b) dew point values for the period of existing the structures. *Source: www.wunderground.com*

3.2 HUMIDITY

In addition to the analysis of the ambient temperature, an observation of humidity was also performed for a period of 1, 3 and 6 months before the measurement of the bridges. The results of this observation are shown in Table 8 through the average of daily maximum values. The average of daily maximum humidity for a period of 6 months is in range of 87.7%, 92.4% and 91.9%. In the case of a period of 1 month the average of daily maximum humidity is almost constant between 91.8% and 92.1%.

Table 8 Mean humidity of maximum daily values

Observation Period [months]	Average of daily maximum values [%]		
	2017	2020	2022
1	92.1	91.8	91.95
3	85.3	92.9	90.0
6	87.7	92.4	91.9

The maximum, minimum and average humidity on the location in the period of existing the structures, almost 5 years, (1.1.2017-31.5.2022) is presented on Fig. 11. This figure shows that the average humidity during the whole period is almost 70%.

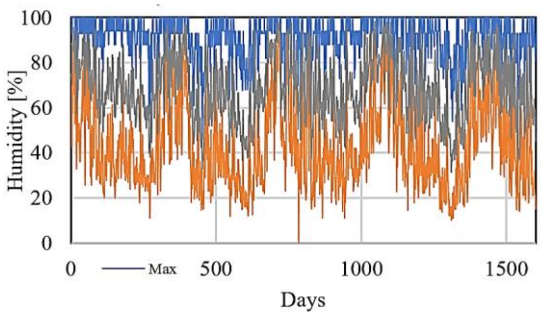

Figure 11. Maximum, minimum and average humidity [%] on the location
Source: www.wunderground.com

3.3 WIND SPEED

Wind speed is the characteristics of air movement that can have influence of the dynamic characteristics of bridge structures, especially of long span bridges. The wind conditions have no significant influence of the considered reinforced concrete frame bridges, but it is taken into account in this investigation. Herein, only maximum and average wind speed at the location is presented in the period of bridges existence (Fig. 12).

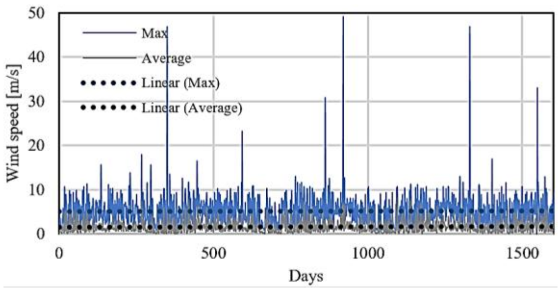

Figure 12. Wind speed at the location of bridges
Source: www.wunderground.com

From the Fig. 12 it can be concluded that on the location of the bridges, the maximum wind speed is almost 50 m/s, but the average speed is 1.5m/s.

4. CONCLUSIONS

The objective of this study is to investigate the environmental effects on the dynamic characteristics of two base-isolated highway monolithically constructed frame overpasses. The dynamic characteristics of the structures are defined using large scale ambient vibration testing. To consider the difference in the dynamic characteristics of the structures, three measurements were performed to both bridges. The first measurements were realized after the construction of the structures, in 2017; second one 3 years later, in 2020; and the last one 2 years after the second measurements, in 2022.

The ambient vibration tests were conducted under the environmental excitations in the bridges and the dynamic characteristics of structures were accurately extracted. Both overpasses were exposed on only environmental atmospheric conditions. They are still not in use, so they were no exposed-on service loads. From the obtained results and the environmental investigation, it can be stated that:

- There are differences in the results from the performed ambient vibration testing in three periods of the existing the structures. Since they are not in use and are no exposed to service loads, it can be concluded that the environmental conditions have influence of the dynamic characteristics of the structures.
- The natural frequencies of both structures are higher with the time. Especially in longitudinal and transversal directions. The difference in vertical direction is almost the same.
- The difference between the measured frequencies from first two measurements is bigger than the second and the third measurement, that means that the structure is getting stabilized.
- Temperature and humidity have influence of the dynamic characteristics of the structures.
- Wind speed do not have influence of the dynamic characteristics of the structures.

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