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STUDY OF THE EFFECTS OF NATURAL AND MAN-MADE ORIGIN ON THE TECHNICAL CONDITION OF ARCHITECTURAL MONUMENTS

Oleg DEDOV[1*], Maksym VABISHCHEVYCH [1], Oleh SKORUK[1], Grzegorz TWARDOWSKI[2]

[1] Kyiv National University of Construction and Architecture, 31 Povitroflotskyi Avenue, Kyiv, 03037, Ukraine
[2] Cracow University of Technology, Faculty of Architecture, 24 Warszawska Street, 31-155, Cracow, Poland

Abstract

The results of research into the dynamic characteristics of technical objects under the influence of loads of natural and man-made origin are presented. The object of research is the phenomenon of propagation of vibrations in the load-bearing elements of construction structures. One of the problems in the inspection and monitoring of construction objects is the assessment of the dynamic action on the load-bearing elements of the structure. The external influence of dynamic phenomena of natural and man-made origin on the condition of the load-bearing structures of the Cathedral "Sophia of Kyiv" was studied. The revealed phenomena of the transmission of vibrations of the general system of the building made it possible to formulate the reasons for the appearance of defects. The obtained research results can be used in the development of numerical and experimental methods and algorithms for assessing the technical condition of load-bearing elements of buildings and structures under the action of dynamic loads of various sources.

***Keywords**: Inspection of the structure; Vibration diagnostics; Natural frequencies of oscillations; Form of oscillations; Dynamic load; Finite element model*

Introduction

In modern conditions, trends in the creation of new construction sites are aimed at the use of the latest technologies and allow construction work to be carried out in densely built-up areas. As a rule, the interaction between existing structures and built objects cannot be properly analyzed. Therefore, there are static and dynamic effects on existing structures from factors of various nature. Special attention should be paid to architectural structures that have a historical monument and are subject to protection. The problematic issue is the evolutionary destruction of load-bearing structures and finishing materials under the action of dynamic loads. In cases where the factors (causes) of dynamic influence are unknown, the task becomes somewhat more complicated. First of all, it is necessary to determine the sources of such influence, especially this applies to complex systems where there are several potential sources, and not a single vibration source, but a combination of several, may be decisive.

Cultural heritage objects that are in an emergency or close to emergency condition are a special case [1]. Sophia Cathedral of the National Reserve "Sofia of Kyiv" in Ukraine also

* Corresponding author: diedov.op@knuba.edu.ua

belongs to such objects. During preliminary inspections of the building, a large number of deformations in the inner and outer walls were found as a result of past events. In connection with the complex of existing and new vibration loads, a hypothetical assumption is proposed about the possible influence of dynamic phenomena on the building of the Cathedral. One of the assumptions is the impact of dynamic phenomena due to a complex multi-layered soil foundation. In particular, the article [2] shows the modeling of the soil massif under the action of dynamic influence. The paper considers a multilayer array composed of non-homogeneous elements that are approximated by discrete parameters within a separate layer. According to the results of the research, the authors revealed the effect of the presence of layers with different dynamic characteristics on the intensity of the passage of seismic waves. In work [3], an assessment of the possible transfer of energy through the soil massif to the foundations of buildings located next to the railway track during the movement of trains was carried out. According to the results of experimental studies, multi-frequency oscillations were recorded by the researchers, which could potentially lead to damage to the structures of the buildings. One of the possible solutions to reduce the man-made impact on the foundations is presented in [4]. A complex dynamic system "source of vibrations - building structure" is considered here, which takes into account the operation of a damping element designed to reduce the transmitted energy. quenching. In [5], based on the received oscillogram records, a method of identifying and analyzing important points of the frequency spectrum of oscillations is proposed. Measuring the dynamic characteristics of systems in order to detect defects in structural elements is devoted to [6, 7]. These works present the methodology of applying experimental studies of vibration and their processing. The authors note the presence of noise phenomena that interfere with the assessment and accounting of these phenomena, it is proposed to implement them with the help of mathematical processing. Determination of the parameters of the dynamic systems of buildings made of metal structures, taking into account the existing defects, is presented in the paper [8]. The authors proposed a method of using field studies of vibration to clarify the dynamic characteristics of the calculation model. Studies of the influence of man-made vibration in the conditions of urban development based on the measurement of vibration accelerations are given in [9]. The authors investigated the amount of energy transfer to the monitoring facility depending on the type of soil base and the distance to the drilling site. The authors [10] considered the method of analysis of wave propagation and transmission ratio in building structures. Wave speed and transfer functions were accepted as criteria for evaluating local defects. The authors apply the path of wave propagation in structures by comparing experimental (measured values) and nominal values using the example of a 14-story residential building and a 64 m long pedestrian bridge. As for the measurement tools when conducting experimental research, different types of sensors are used both to determine static parameters and dynamic. the most common characteristics are vibration acceleration and vibration speed, but along with it, laser and optical devices can be used for remote measurement [11]. Determination of factors and their influence on the life cycle of historical monuments is the object of research of this article. In particular, St. Sophia's Cathedral is a monument of architecture, history, and monumental art (the first half of the 11th century - the end of the 17th century - the beginning of the 18th century, the end of the 19th century) of national importance. It is part of the UNESCO world cultural heritage site "Kyiv: Saint Sophia Cathedral and adjacent monastic buildings, Kyiv-Pechersk Lavra".

Materials and methods

Experimental studies were carried out under the operating conditions of the research object. The main task of the study was to establish the factors of dynamic influence on the load-bearing structures of the building and to predict the potential causes of the development of structural element defects.

The values of the natural frequencies of oscillations are chosen as the criterion for assessing the state of the load-bearing structures.

The method of discrete Fourier transformation was used for the numerical processing of the obtained vibrograms of the vibrations of the research object at the control points.

The finite element model of the building frame fragment is built according to the well-known rules of construction mechanics. Static and modal analysis of structures is performed in a linear setting using the "Scad Office" computer complex, which is based on the use of the finite element method.

Results and Discussions

Sophia Cathedral (Fig. 1) was built in 1017 and has been in use for more than 1000 years. Since then, the building has experienced partial reconstructions, local destruction and political troubles. At the time of inspection, it is operated in normal mode. The cathedral is an important historical and architectural monument of world significance.

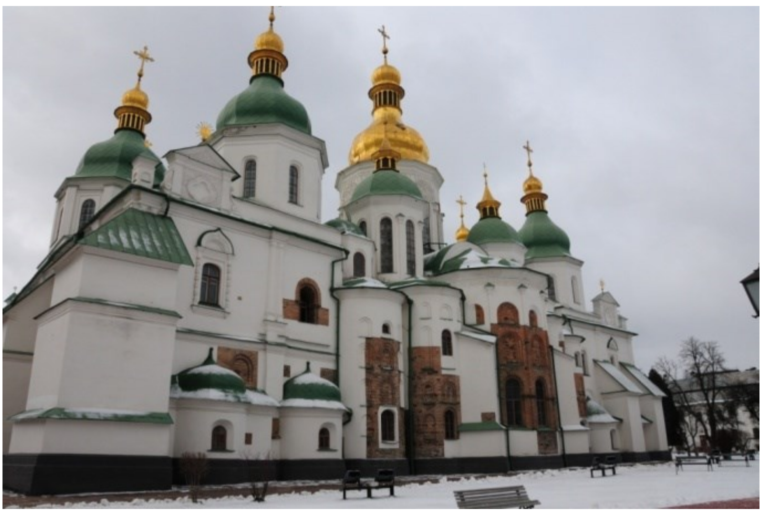

Fig. 1. View of St. Sophia Cathedral of Kyiv from the east side. Kyiv, st. Volodymyrska, 24

Experimental studies were carried out under the conditions of operation of the facility. Vibration acceleration sensors were used to measure and obtain real values of vibrations at various points of the building.

Conducting research was based on an approach based on the hypothesis of considering systems of a complex structure, which has a dynamic influence, as a single system with its corresponding dynamic characteristics. Within such consideration of the system, it is necessary to identify and evaluate the impact of various origins. The following factors were identified among the potential impacts on the construction of the building:

- impact of road transport:
- impact from mass events outside the building;
- impact from mass events within the building.

The implementation of research was carried out by determining integral dynamic parameters with further analysis and establishment of cause-and-effect relationships.

Simultaneous registration of dynamic parameters by several autonomous or networked devices allows you to control the quality of the received data and ensure their reliability.

To determine the microseismic background of the environment, measurements were performed at several levels in height, as well as near the structure on the surface.

Setting up the main reference point for the base station on the load-bearing wall of the second floor and determining the level of the microseismic background at the reference point.

At the next stage, recordings of dynamic processes were made on other structural elements simultaneously with recordings of the basic reference point of measurements (Fig. 2). The implementation of research was carried out by determining integral dynamic parameters with further analysis and establishment of cause-and-effect relationships.

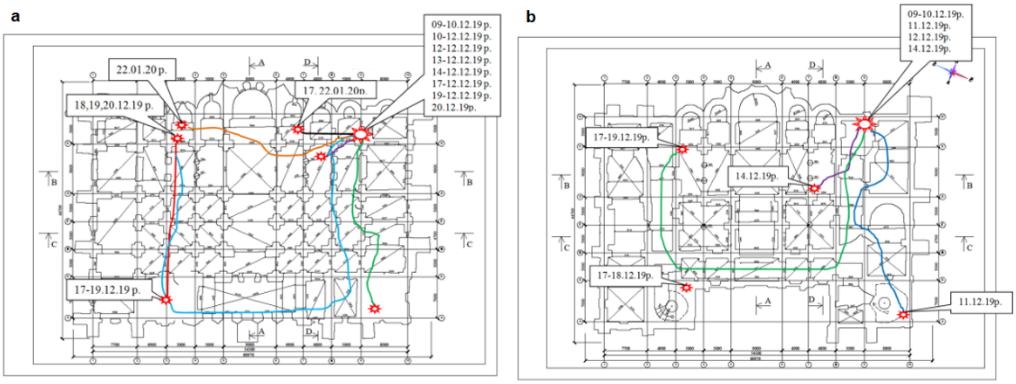

Fig. 2. Scheme of placement of measuring sensors and registration of measurements over time

In the course of the study, records of continuous fixation of dynamic action parameters were used directly on the load-bearing structures of the studied object and on the periphery of the territory of the reserve. Thus, the obtained results made it possible to evaluate both external and internal factors influencing the dynamics of the structure.

Thus, the nature of the external impact from land transport (Fig. 3) has an insignificant effect, which is explained by the presence of fencing structures. Such enclosing structures - masonry, are a barrier to the transmission of vibrations. Spectral analysis (Fig. 4) demonstrates the absence of noise, which is characteristic of the movement of ground transport.

For each level, oscillograms of micro-oscillations of the cathedral were obtained, on the basis of which the natural frequencies of the structure's vibration spectra were determined. Spectral analysis of component recordings of vibration accelerations at different levels made it possible to obtain amplitude-frequency characteristics and determine the main harmonics of the structure's vibrations.

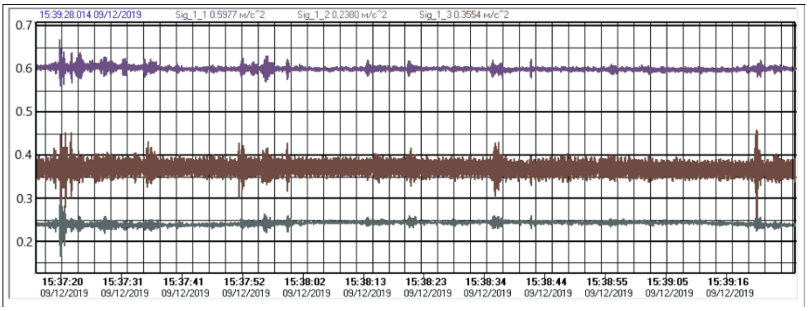

Fig. 3. Oscillograms of XYZ records, dynamic impact from transport

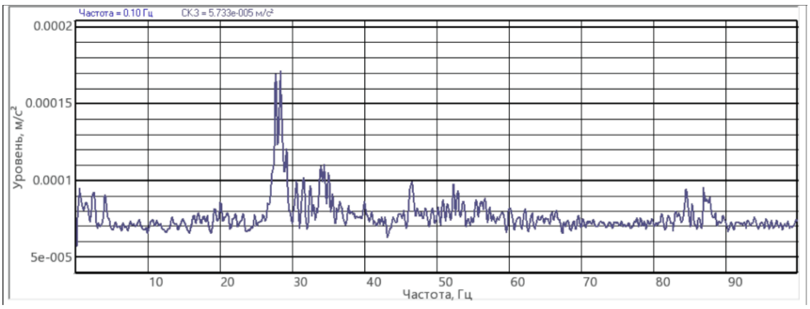

Fig. 4. Spectrogram of records X, dynamic impact from transport

The registered data show the presence of dynamic action with a clear periodicity (Fig. 5), which are influenced by man-made nature, since the vibrogram has a record during intensive life activity. Analysis of such a signal (Fig. 6) shows a dynamic effect in the range of often 35-60Hz. This is the nature of action of underground transport. And the recorded impact indicates the transfer of energy through the ground mass to the load-bearing structures of the building. Holding mass events during the celebration is another source of dynamic influence on the building of the Cathedral. The authors obtained the results of such an influence during the celebration of St. Nicholas Day (Fig. 7).

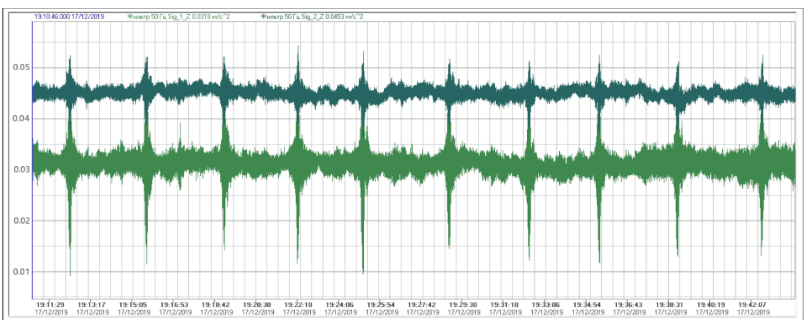

Fig. 5. Oscillograms of recordings, control points TC0, TC2

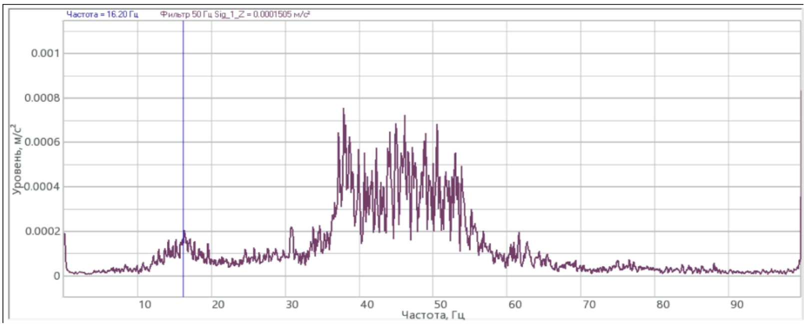

Fig. 6. Spectrogram of records, control point TC0

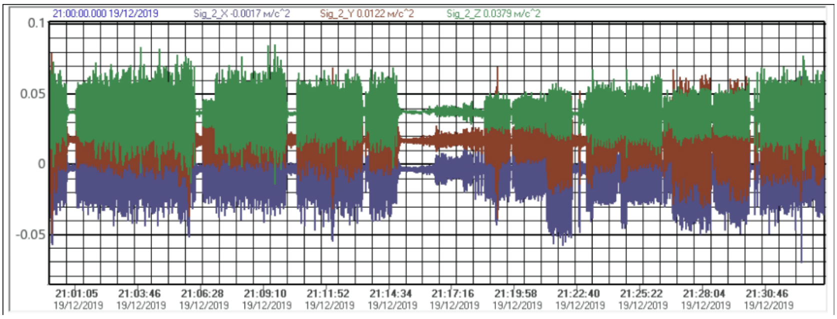

Fig. 7. Oscillograms of recordings, TC0 control points

The analyzed oscillations of the structure revealed a different spectrum of frequencies (Fig. 8). Here you can see a shift of the frequency spectrum towards higher oscillation frequencies. This is explained by the presence of a sound signal in the form of loud music and chants. To compare the impact on the construction of the Cathedral, a comparative analysis of the identified potential impact factors was carried out (Fig. 9).

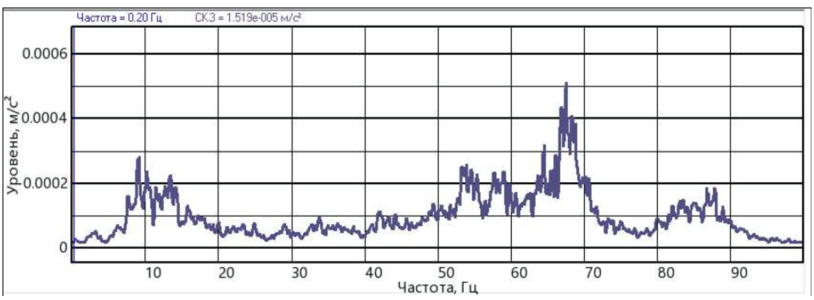

Fig. 8. Spectrogram of records, control point TC0

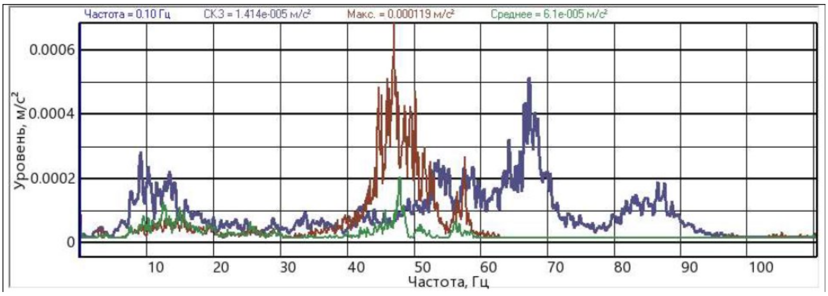

Fig. 9. Comparative analysis of spectra (frequency range 0–100Hz): green line— with minimal influence of dynamic phenomena; brown line— with man-made influence; blue line — during mass events in the cathedral

The obtained results demonstrate the presence of oscillations in a wide range of oscillations. That is, the structure of the building perceives multi-component fluctuations of various nature. The numerical values of the recorded effects (Table 1) do not exceed the permissible values. But the presence of wide-band oscillations can be the reason for the occurrence of resonance-like phenomena of individual elements of structures, including decorated layers.

Table 1. Experimental values of dynamic parameters under the influence of factors of potential sources

Impact factor	Frequency range, (Hz)	Vibration acceleration, (m/s^2)
	1 – 10	$(1.5\text{-}2.2)\cdot 10^{-5}$
Night recording	10 – 30	$(1.9\text{-}10)\cdot 10^{-5}$
	30 – 70	$(7.3\text{-}8.4)\cdot 10^{-5}$
	1 – 10	$(11\text{-}12)\cdot 10^{-5}$
Road	10 – 30	$(10\text{-}15)\cdot 10^{-5}$
	30 – 70	$(13\text{-}15)\cdot 10^{-5}$
	1 – 10	$(2.2\text{-}4,5)\cdot 10^{-5}$
Underground	10 – 30	$(2,1\text{-}6,8)\cdot 10^{-5}$
	30 – 70	$(9,8\text{-}188)\cdot 10^{-5}$
	1 – 10	$(3.4\text{-}19)\cdot 10^{-5}$
Activities	10 – 30	$(2,1\text{-}6,8)\cdot 10^{-5}$
	30 – 70	$(9.2\text{-}12)\cdot 10^{-5}$

To investigate the possibility of such phenomena, a mathematical calculation model was created, executed in the Scad Office software complex. The model was built based on the results of the geometric dimensions of St. Sophia Cathedral and taking into account the properties of materials and the results of field surveys and geological investigations. The main internal elements of rigidity are central pillars, parts of walls, arched structures, overlapping choirs, corner fragments of walls. To investigate and confirm the hypothesis about the possibility of resonance phenomena, a fragment of the structure was considered (Fig. 10 and Table 2).

Forms of oscillations and their frequencies are established on the basis of numerical simulation. According to quantitative indicators, such forms of oscillations can fall into the range of experimental frequencies. Such regimes are dangerous from the point of view of the occurrence of short-term but close to resonant phenomena. Together with destructive processes, this can be the main reason for the destruction of the decoration layer with applied frescoes.

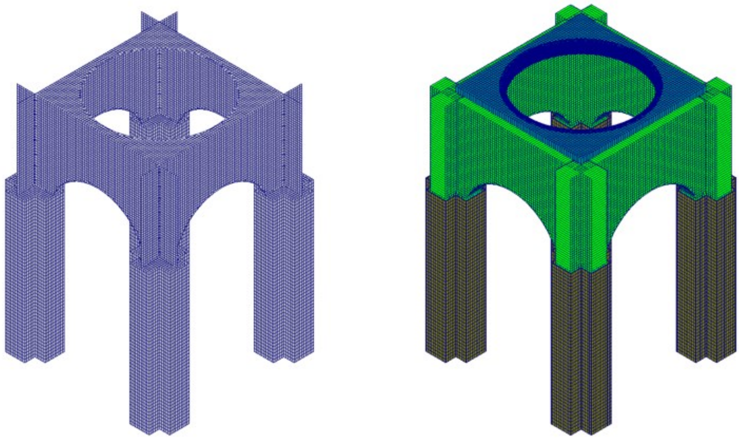

Fig. 10. FEM of a fragment of the cathedral

Table 2. Modeling of tinting (general movement of 75% of the nodes on the contact surfaces of the tinting ball and integral stops)

Loading		Mode number	Frequency		Oscillation period	Modal masses (%)		
			rad/sec	Hz	sec	X	Y	Z
3	Modal	1	53,71	8,58	23,06	84,67	0,01	0,
		2	71,85	11,39	17,29	0,	0,	0,
		3	143,83	22,92	8,58	0,	0,	0,
		4	170,41	27,14	7,31	0,	0,	0,
		5	259,97	41,34	4,78	0,	0,	42,75
		6	293,29	46,68	4,22	0,47	0,	0,
		7	293,29	46,68	4,22	0,	0,47	0,
		8	306,79	48,79	4,08	0,	0,	0,
		9	333,36	53,01	3,66	1,93	1,26	0,
		10	333,36	53,01	3,66	1,26	1,93	0,
			Sum of modal masses			88,35	88,35	42,75

Thus, according to the obtained results, the vibration reactions of the main elements of the building have a lower level than expected, given the existing deformations of the main structures of the building, which were detected during instrumental surveys. The external condition of the main structures is stable, the dynamics of the further development of deformations is not visible, as evidenced by observations and static monitoring. On this basis, the conclusion was drawn: the load-bearing structures are in normal condition, the existing damage in the Cathedral does not affect the safety and reliability of the historical building, due to the mass of the building, its geometric dimensions in plan, developed sections of ordinary elements, the vibration situation has a limited effect on the strength and stability of the main elements of the object. However, visual inspection of the inner and outer walls revealed defects in the form of cracks in the fresco painting, which dates back to the beginning of the building's operation and is a priceless thousand-year-old artistic monument. During a selective inspection of the frescoes, the main defects are associated with detachment from the vaulted base. The process takes place mainly in the upper part of the Cathedral. In these places, destructive processes develop more intensively, which accelerate the destruction of the painting and its foundations. One of the reasons for the appearance of such defects is possible dynamic processes, under the action of which phenomena similar to resonance occur in individual elements of the decoration and, in combination with other factors, affect the development of defects.

Conclusions

The results of the conducted research proved the existence of a dynamic influence on the building of the Cathedral. The values of the dynamic load of man-made fires have been established.

According to the obtained results, the vibration reactions of the main elements of the building have a lower level than expected, given the existing deformations of the main structures of the building, which were detected during instrumental surveys. The external condition of the main structures is stable, the dynamics of the further development of deformations is not visible, as evidenced by observations and static monitoring. On this basis, the conclusion was drawn: the load-bearing structures are in normal condition, the existing damage in the Cathedral does not affect the safety and reliability of the historical building, due to the mass of the building, its geometric dimensions in plan, developed sections of ordinary elements, the vibration situation has a limited effect on the strength and stability of the main elements of the object. The conducted research has limitations in the part of experimental determination of the contribution of high frequency oscillations and the nature of their action on individual elements of structures. The possibility of the occurrence of dynamic processes, under the action of which phenomena similar to resonance occur in individual elements of the decoration, is confirmed by the modeling of a fragment of the decoration. Such a hypothesis needs experimental confirmation, which is planned as a further development of this problem. The limited number of experimental studies performed can be attributed to the shortcomings of this study. After all, the structure is a complex dynamic system, which exhibits many frequency responses to external energy sources. This is especially important in the emergency situations that are taking place in Ukraine today.

References

[1] L.D. Mollá, M. Sagarna, A. Zabaleta, A. Aranburu, I. Antiguedad, J.A. Uriarte, *Methodology for assessing the vulnerability of built cultural heritage*, **Science of the Total Environment**, **845**(1), 2022, Article Number: 157314. DOI: 10.1016/j.scitotenv.2022.157314.

[2] S. Skurativskyi, O. Kendzera, S. Mykulyak, Y. Semenova, I. Skurativska, *Seismic response assessment of a weakly nonlinear soil deposit*, **Journal of Applied Geophysics**, **211**, 2023, Article Number: 104970. https://doi.org/10.1016/j.jappgeo.2023.104970.

[3] V.G. Cleantea, M.J. Brennana, G. Gatti, D.J. Thompson, *On the spectrum of rail vibration generated by a passing train*, **Procedia Engineering**, **199**, 2017, pp. 2657–2662. DOI: 10.1016/j.proeng.2017.09.532.

[4] P. Cacciola, N. Banjanac, A. Tombari, *Vibration Control of an existing building through the Vibrating Barrier*, **Procedia Engineering**, **199**, 2017, pp. 1598–1603. https://doi.org/10.1016/j.proeng.2017.09.065.

[5] M. Kavyanpoor, S. Shokrollahi, *Dynamic behaviors of a fractional order nonlinear oscillator*, **Journal of King Saud University – Science**, **31**(1), 2019, pp. 14-20. https://doi.org/10.1016/j.jksus.2017.03.006.

[6] V.N. Patel, N. Tandon, R.K. Pandey, *Vibrations Generated by Rolling Element Bearings having Multiple Local Defects on Races*, **Procedia Technology**, **14**, 2014, pp. 312–319. https://doi.org/10.1016/j.protcy.2014.08.041.

[8] D. Giagopoulos, A. Arailopoulos, V. Dertimanis, C. Papadimitriou, E. Chatzi, K. Grompanopoulos, *Computational Framework for Online Estimation of Fatigue Damage using Vibration Measurements from a Limited Number of Sensors*, **Procedia Engineering**, **199**(7), 2017, pp. 1906–1911. DOI: 10.1016/j.proeng.2017.09.424.

[9] A. Rallu, N. Berthoz, S. Charlemagne, D. Branque, *Vibrations induced by tunnel boring machine in urban areas: In situ measurements and methodology of analysis*, **Journal of Rock Mechanics and Geotechnical Engineering**, **15**(1), 2022, pp. 130-145.

[10]C-Man Liao, Y.S. Petryna, *Damage Assessment of Civil Structures Using Wave Propagation Analysis and Transmissibility Functions* (Chapter), **Experimental Vibration Analysis for Civil Engineering Structures**, 2023, pp. 3–13. DOI:10.1007/978-3-030-93236-7_2.

[11] T. Wu, L. Tang, P. Du, N. Liu, Z. Zho, X. Qi, *Non-contact measurement method of beam vibration with laser stripe tracking based on tilt photography,* **Measurement**, **187**, 2022, Article Number: 110314. https://doi.org/10.1016/j.measurement.2021.110314.

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