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Modern risk assessment of the influences of natural and military man-made factors on the state of the historical buildings of the Kyiv-Pechersk Lavra

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During its thousand-year history, the Kyiv-Pechersk Lavra has experiences many disasters. At the time when the fight against religion was part of the state ideology, the cathedral and monastery were closed, and its countless treasures were confiscated. Even in the turbulent 1930s, when the bolsheviks destroyed dozens of unique temples and churches in Kyiv, the Assumption Cathedral remained intact. Black days for the age-old shrine came during the German occupation in the fall of 1941. First, the shrine was looted, and many material and artistic valuables were taken. In November 1941, a series of explosions destroyed the main temple of the Kyiv-Pechersk Lavra, which had served as a tomb for the Kiev princes. In February 2022, the war had started again in our country, and modern scientific technology allows us to assess the impact of military events on buildings of Kyiv-Pechersk Lavra from viewpoint of the level of seismic hazard assessment, which have lasted in Ukraine for more than two years, because Kyiv-Pechersk Lavra is listed as a UNESCO World Heritage Site.

The article presents the results of the analysis of the operation of devices for various purposes — from the recording of seismic-acoustic waves, which have a high frequency of natural oscillations, to low-frequency ones, which are recorded by a laser inclinometer.

The article also presents the results of modern automated data processing using various methods — from the spectral method of signal recognition to the modern autopicker method of determining the time of arrival of waves AIC, which allows you to clearly determine the arrival time of vibration waves of various origins — from the formation of cracks in historical buildings of the Kyiv-Pechersk Lavra to vibration waves of technical and natural origin.

Key words: military events, vibration, deformation, velocimeter, laser inclinometers.

Introduction. The National Reserve «Kyiv-Pechersk Lavra» occupies a large area and covers various geomorphological elements. This determines the complexity of the engineering and geological conditions of the territory (the presence of rocks with different physical and mechanical properties at beneath the monuments, erosional disintegration of the terrain, high level of groundwater, etc.) [Rybin et al., 2001; Kendzera et al., 2016; Cherevko, 2021]. The Verkhniay Lavra, located within the loess plateau and the upper

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part of its slopes, is most affected by hidden flooding, subsidence, and suffusion caused by changes in the physical and mechanical properties of loess sands and loams below most structures, under the influence of natural and man-made factors (infiltration of atmospheric precipitation, leaks of clean and wastewater from water-bearing systems, etc.). Buildings located on the edge of the slopes are affected by landslides. Landmarks of Nyzhnia Lavra, located mostly on slopes on diluvial soils of different properties, brown and variegated clays that can swell and sand, suffer mainly from landslide processes and evident flooding of underground historical caves. They are also affected by hidden flooding, erosion, suffusion, and loosening.

Of the exogenous processes on the territory of the Kyiv-Pechersk Lavra (KPL), flooding is the most common issue affecting 56 monuments, followed by subsidence and landslides (17 monuments a peace) and suffusion affecting 10 monuments [Cherevko, 2018]. The typical signs of structural deformations they cause are cracks and uneven subsidence. Under certain conditions, these can lead to partial destruction. Currently, four monuments are in an emergency state, as determined by the Permanent Commission for Technical and Economic Safety and Emergency Situations of the Kyiv City State Administration. Approximately 20 monuments are in an unsatisfactory technical condition. Man-made accidents involving water-carrying engineering networks exacerbate these issues by causing soil over wetting, subsidence, and monument destruction. Since February 24, 2022, the start of active hostilities due to armed aggression by the Russian Federation, the historical sites have also suffered from blast waves from air strikes. For instance, during the shelling on December 16, 2022, a rocket impact caused significant vibration that damaged historical buildings. The vibrations were strong enough to dislodge installed fixtures from cracks in the walls. These vibrations can potentially activate erosive-gravitational and geodynamic processes on sandy slopes in the reserve. In such loose soils, dynamic loads can displace soil particles, causing shear deformations, changes in porosity, and, under undrained conditions, changes in pore pressure. These factors could lead to shear displacements and liquefaction on the slopes.

A monitoring network was established in the reserve in 2009 to continuously observe (a necessary condition according to DSTU-NB V.1.2-17:2016) the technical condition of architectural monuments. This includes monitoring deformation dynamics, moisture levels in buildings, microclimatic changes, surface movements, and the development of unfavorable engineering and geological processes. However, there is a need to enhance this monitoring system by expanding the observation network and deploying highly accurate, sensitive equipment [Britsky et al., 2023]. This would confirm the influence of vibrations on deformation processes, monitor the expansion of existing cracks [Chalyi et al., 2023], and detect new ones. For example, the Belfry of the Great Lavra, which is already tilting westward and showing increasing inclination, requires an eight-component laser magnetometric inclinometer with automated data processing to monitor its stability.

Recording of military events in the city of Kyiv on the territory of the KPL. With the beginning of full-scale hostilities as a result of the armed aggression of the Russian Federation, new man-made effects of a military nature appeared on the monuments of the reserve. The spread of explosive waves when air targets are shot down or missiles are hit can manifest in the deterioration of the monuments' technical condition, preservation, and operation. Dangerous phenomena in the structural elements of monuments as a result of these or other processes require additional detailed and comprehensive analysis based on special approaches and devices.

To do this, there was installed, within the framework of NRFU project No. 2022.01/0209 «Comprehensive study of the geoecological state of preservation of objects of historical and cultural heritage of the National Reserve «Kyiv-Pechersk Lavra» in the conditions of military operations», a complex system of seismometers and lasers developed by LTD «RODEN». These devices recorded various military and natural events during the first period of operation from August 2023 to February 2024.

An important result was the determination of the presence or absence of damage to structures all historical buildings KPL by enemy missiles in the city of Kyiv. One of the most dangerous attacks by missiles and drones in the city of Kyiv in 2023 took place on the night of August 29—30 this year. The successful destruction of these enemy objects by the air defense forces of the Armed Forces of Ukraine did not damage the Assumption Cathedral of the KPL, where the equipment was located.

An infrasound event of the «technical explosion» type was also recorded on the night of December 21—22, 2023 at Solomyansky district, V. Lobanovskyi avenue, 4-B, 50°25′19″ N 30°27′45″ E, type of weapon: kamikaze drone Shahed (Fig. 1). The distance from the explosion to the observation point in building No. 3 of the KPL is 6738.52 meters. Records of three components of the infrasound waves from the explosion are presented in Fig. 2.

The massive missile attack on Ukraine on January 23, 2024 began in the morning of January 23 as part of the Russian invasion of Ukraine. Russian troops launched a missile attack on Ukraine. Cruise and ballistic mis-

Fig. 1. A 26-story building in the Solomyanskyi district of Kyiv, damaged by debris from a downed Russian drone on the night of December 21—22, 2023. On the left is a damaged part of the house.

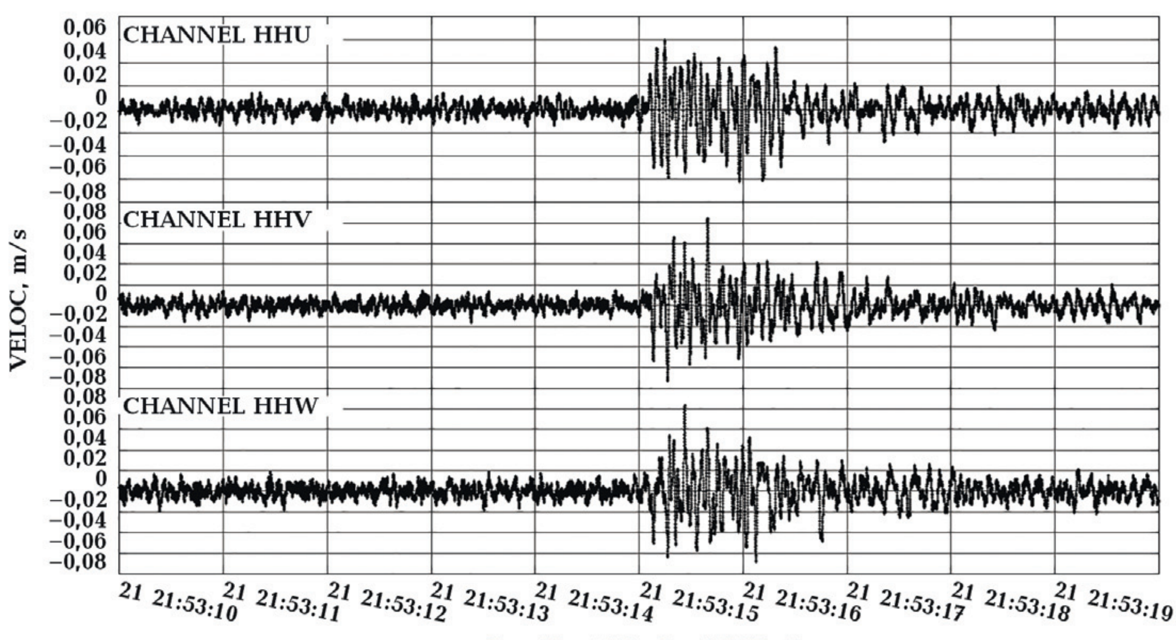


Fig. 2. Three components of an infrasound event of the «technical explosion» type, which occurred on the night of December 21—22, 2023, on the top floor of a 26-story building in the Solomyansky district of Kyiv as recorded in Lavra.

siles were used, Ukrainian air defense forces shot down 21 missiles out of 41. Kyiv, Kharkiv, Pavlograd, Balaklia and Shostka were fired upon. 12 Tu-95MS aircraft launched Kh-101/Kh-555 cruise missiles from the Caspian Sea. Later, Tu-22M3 bombers took off, which also launched cruise missiles. The first groups of rockets flew over Sumy Oblast. After the maneuvers over Vinnytsia and Zhytomyr oblasts , most of them flew to Kyiv. It was in Kyiv that air defenses were deployed and explosions were heard. To analyze the forms of recordings of these events on the territory of the KPL, from the complete set of devices that were located in building No. 3 of the KPL, only three are selected: 3D velocimeter (hereinafter, device for KPL), 1D velocimeter (hereinafter device 1D) and 1D a microphone (one-dimensional device for fixing sound propagation) that was designed to capture sound from cracks. The general forms of recordings of many processes of the «war events» type during the shelling of Kyiv recorded on the territory of the KPL with this kit, are presented in Fig. 3.

On January 23, 2024, Kyiv was shelled for almost one hour (see Fig. 3). Various military technical events were recorded during this time.

Therefore, the optimal choice from this set of diverse events may be to focus only on non-standard events that are absent in classical seismology, whose origin is specifically linked to assessing their level of danger to the structures of the KPL. This approach could also be applied to other structures in the city of Kyiv during the war.

The selection of specific events within a shortened time interval in the area of the 3D and 2D velocimeters, which are technically capable of recording infrasound data from these events, simplifies the analysis by focusing on selected time intervals of the recorded data.

This simplified approach allows for the exclusion of sound recordings of the 1D microphone records from the analysing, because the velocimeters independently recorded the infrasound signals. (Fig. 4, 5).

Comparative analysis of records in Fig. 4, 5 shows that, according to the results of the spectral transformation in the time domain, it is possible to identify different types of events that differ significantly from each other precisely in the frequency domain and that are purely natural, technical or military events of various types. To test the method of spectral

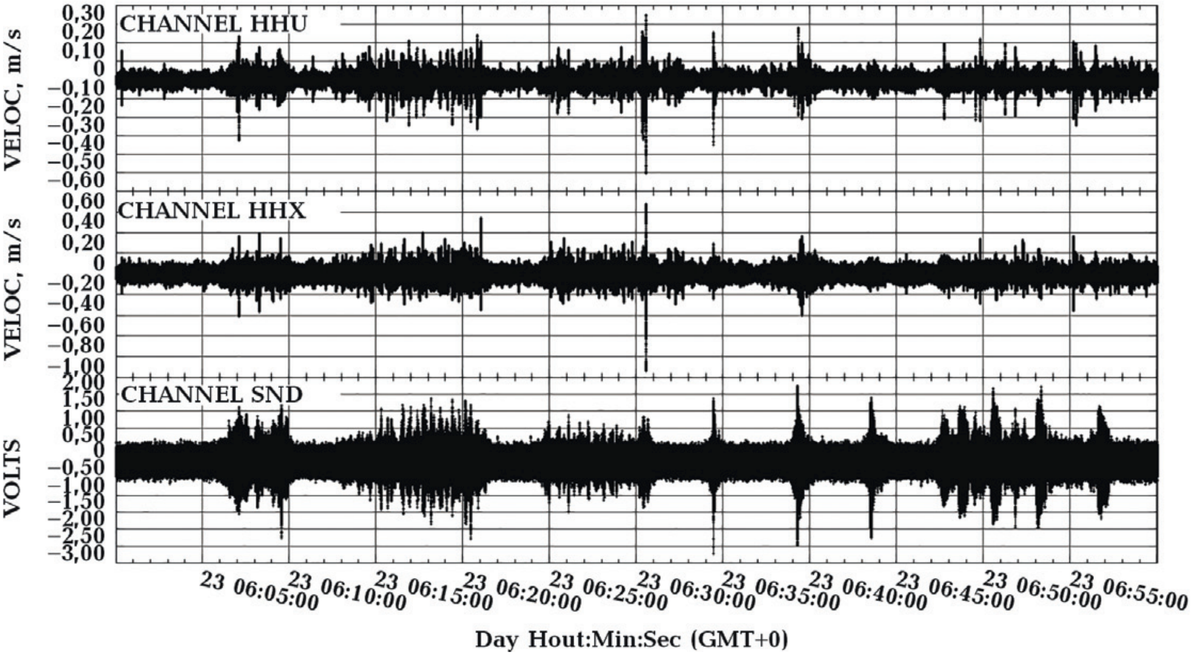
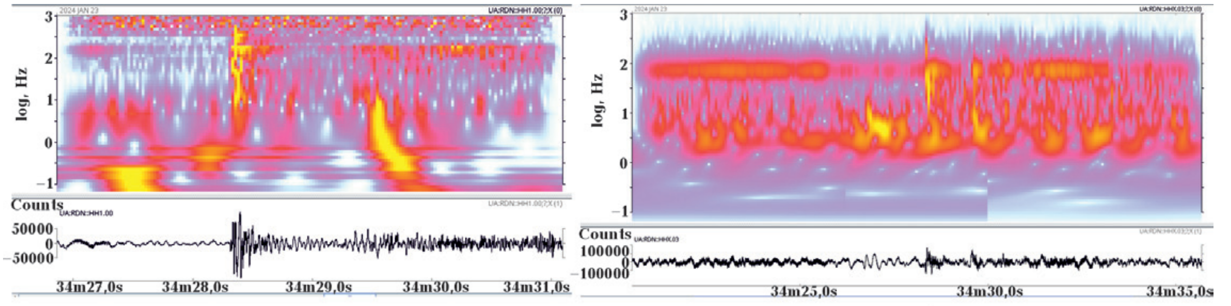


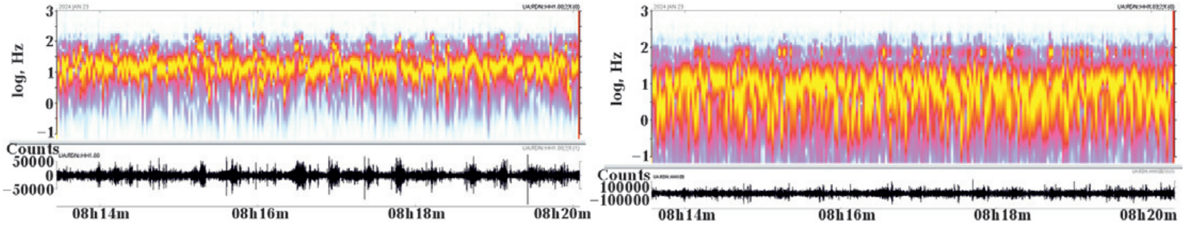
Fig. 3. General forms of recordings of various types of military events during the shelling of the Kyiv lasting one hour, which were recorded by three different devices — two different velocimeters 3D, 1D and 1D microphone.

analysis of these records in the time domain, we will consider two military events, the essence of which is significantly different in the time domain — the flight of the missile itself (Fig. 6) and the operation of the anti-missile anti-aircraft complex (Fig. 7).



a *b*

Fig. 4. Recording of an infrasound signal from an enemy «rocket» type weapon with 3D and 2D devices for measuring speed in building No. 3 of the KPL during the shelling of Kyiv. Spectrogram of one infrasound event in the frequency range: *a* — 6—467 Hz (D3 device for KPL), *b* — 10—549.09 Hz (device 1D).



a *b*

Fig. 5. Fixation of sequences of infrasound signals from the operation of anti-missile anti-aircraft systems by velocimeter-type devices with 3D and 2D code in building No. 3 of the KPL during the shelling of Kyiv. Spectrogram of the infrasound signal from the operation of the anti-aircraft missile complex: *a* — basic frequency 68.37 Hz, shot interval 16:30.118—16:57.938, 25—30 seconds (3D device); *b* — basic frequency 70.06 Hz, shot interval 16:34.328—16:57.124, 20—25 seconds (device 1D).

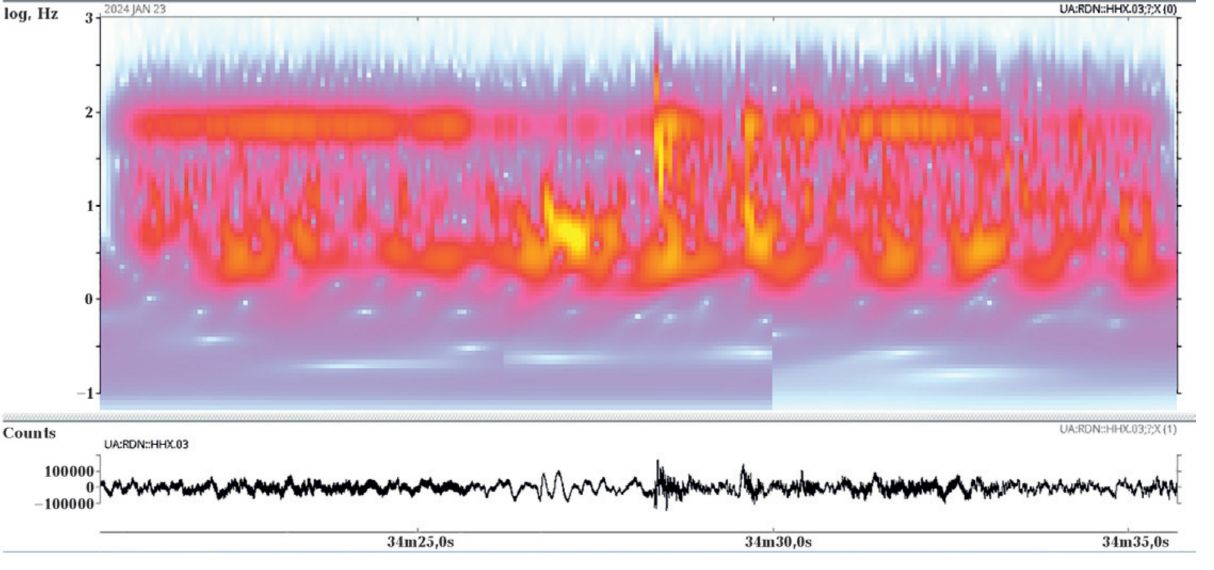


Fig. 6. Spectrogram of one infrasound event of the «rocket flight» type in the frequency range of 10—549.09 Hz, recorded by a velocimeter with the «device 1D» model.

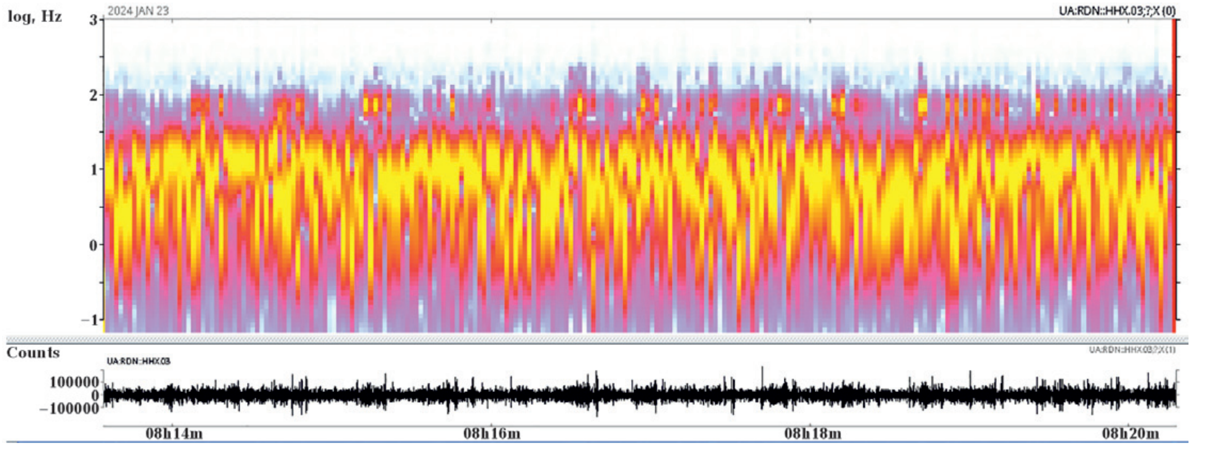


Fig. 7. Spectrogram of sequences of infrasound events from the operation of an anti-missile anti-aircraft complex, with a basic frequency of 68.37 Hz, with a shot interval of 25—30 seconds, recorded by a velocimeter of the «device 1D» type.

An important outcome of this stage of research, focused on recording various military-technical events and assessing their level of danger to the structures of the KPL and other buildings in Kyiv, is the use of special non-standard devices with high sensitivity.

The proposed «1D device» type is designed to address these issues, allowing for the qualitative and accurate recording of various events.

The results of operating this type of device provide a sufficient volume of necessary information for the qualitative analysis of various types of events and their effective processing.

The next main stage within the framework of NFDU project No. 2022.01/0209 was assessing the safety level of the impact of the dynamic, heterogeneous geological structure under the KPL on the condition and stability of its historical buildings. For this, a working 3D model of a laser inclinometer with a Foucault pendulum was used.

Statistical analysis of laser inclinometer data. The next major stage of scientific research into the condition of the KPL introduced a new approach to long-term measurements of ground tilts in various areas of this historic site. This was necessary due to the significant tilting of the KPL Bell Tower, caused by the many underground cavities. For this purpose, a functional working 3D model of a laser inclinometer with a Foucault pendulum was used. (Fig. 8, 9).

Software for the scientific and technical statistical processing of laser inclinometer data was utilized. This approach was necessary because laser measurement systems can detect ultra-low-frequency geophysical signals in the displacement range of 0.0 to 16 Hz,

Fig. 8. General scheme of the 3D laser inclinometer, which was located in the 3rd building of the KPL.

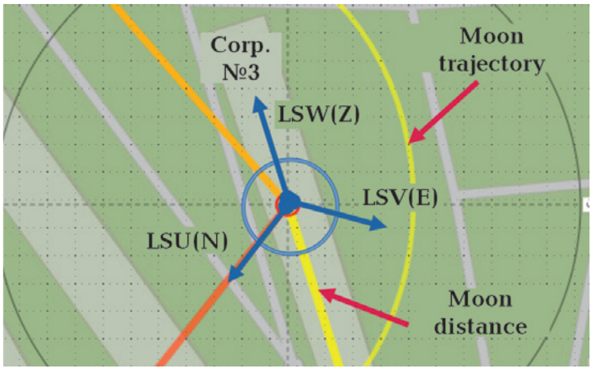


Fig. 9. Own coordinate system of the UVW type for tying 3 lasers to the architectural structure of building No. 3.

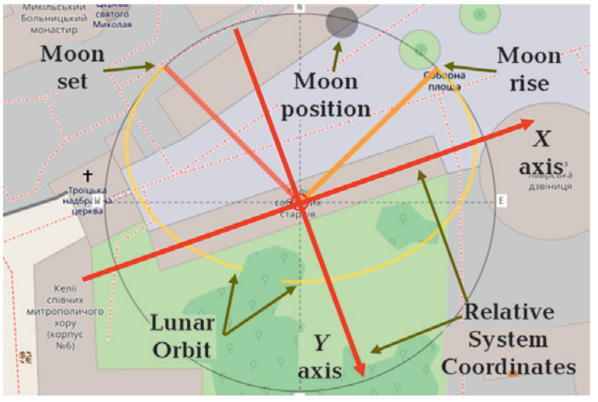


Fig. 10. The relative system of 2D *XY* coordinates of the 3D laser inclinometer to the basic technical UVW coordinate system (see Figs. 8, 9), which is tied to the spatial orientation of building No. 3 of the KPL.

with significant natural Earth noise present between 0.1 and 0.4 Hz. The method of calculating average values helps eliminate random data and focuses attention on the important displacement trends of the form $ax+b$.

These are physically related to long-term dangerous natural low-frequency geophysical processes — the tilts of the soil surfaces where various structures of the KPL stand with big masses of buildings and underground voids beneath them.

The subsidence of these unstable areas in zones with underground artificial and natural voids, along with vertical deformation caused by the gravitational influence of the Moon on the third and fourth buildings of the KPL, may provoke a failure or further subsidence of these historical structures.

The laser 3D inclinometer used to monitor these hazardous processes was situated in the middle section of the third building of the KPL, approximately 60 meters from the Bell Tower.

After tying the 3D laser inclinometer to the architectural structure of relative locations, we had to develop special software to ensure the transition from the coordinate system of the 3D laser inclinometer to the *XYZ* coordinate system, and this 3D coordinates system is already directly related to the 2D location structure of the 3rd KPL building. For this, we used a special matrix for the UVW coordinate system. As part of these results, the 3D laser inclinometer records have already been modified from the UVW system to the *XYZ* system, the *XY* axes of which are tied to the spatial 2D orientation of the case No. 3 (Fig. 10), for scientific statistical analysis.

The result of the statistical processing of the 3D laser inclinometer record in the *XYZ* system is based on the methodology described in https://www.gnu.org/software/gsl/doc/html/statistics.html, and is presented numerically in Table.

The ten approaches for the statistical evaluation of laser data from a 3D laser inclinometer allow for assessing its operational

Statistical Measures (Mean, Standard Deviation, and Variance) of 1D Vector Laser Data

Number	Description	Code	Example 1D vector values
1	Simple middle value	Sample_mean	21.176509
2	Estimation of the deviation of the mean value	Estimavarning	4.484054
3	Maximal value data	Largest_value	31.722795
4	Minimal value data	Smallest_value	14.354380
5	Average value for the period	Median_value	21.074829
6	Standard deviation	Standart_deviation	2.117558
7	The square root of the mean value	Root_mean_square	21.282090
8	The standard deviation of the square root of the mean	Standart_deviation_mean	0.035055
9	A measure of the asymmetry of the probability distribution of a real random variable relative to its mean	Skew_value	0.488990
10	A measure of «tailedness» of the probability distribution of a real random variable	Kurtosis_value	0.759516

quality and technical capability, ensuring the application of correct analytical methods to evaluate the performance and safety levels of phenomena recorded by the inclinometer itself:

– angle tilts of soil surfaces in areas where various KPL structures are located;

– subsidence in zones of underground artificial voids created by the monks of the KPL monastery;

– vertical deformation resulting from the gravitational influence of the Moon on the relative positions of the two hulls of the KPL — the 3rd and 4th (see Fig. 4).

Evaluation of the sensitivity of the laser 3D inclinometer and analysis of its data streams.

To obtain real geophysical information regarding displacements measured by the 3D laser inclinometer, calibration work was conducted to assess the sensitivity of the device, ensuring confidence in the levels of its required dynamic range. The received calibration data indicate that the dynamic range enables high-precision laser displacement measurements within the range of nanometers to tens or hundreds of microns.

The following three coefficient values were kept for recalculations of laser measurement data from ADC digitizing units, on which the laser works in microns at different frequencies:

– MKM/ADC: 0.0000797614014 For Freq: 22.718800 Hz;

– MKM/ADC: 0.0000791975296 For Freq: 21.718800 Hz;

– MKM/ADC: 0.0000937269500 For Freq: 20.718800 Hz.

The middle value is 0.00008422862680 MKM/ADC — 8.42286E-05.

The total operating time interval of the 3D laser inclinometer in the third building of the KPL lasted from 2024-01-11 13:06:31 to 2024-03-03 12:06:23 (Fig. 11) and amounted to approximately 51.95 days or 1246.997 hours. In this figure (Fig. 11), we can observe the following:

– *XYZ* channels (top three), which were

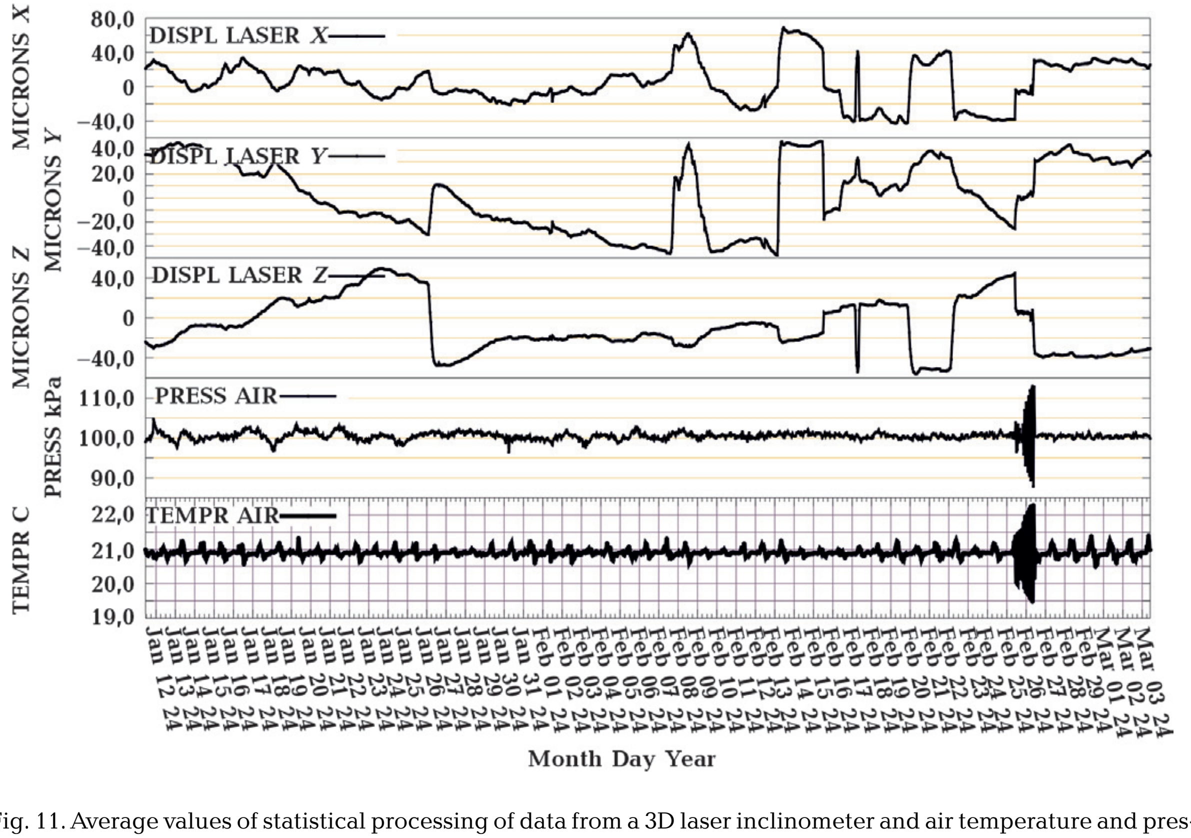


Fig. 11. Average values of statistical processing of data from a 3D laser inclinometer and air temperature and pressure gauges at the observation point of the third building of the KPL (see Fig. 8, 9, 10).

calculated from the UVW channel data (see Fig. 9, 10);

– average values of air pressure and temperature — two from below.

As shown in Fig. 11, the use of these two high-precision digital recorders of atmospheric parameters was crucial for monitoring external thermodynamic factors that could affect the operation of the technical optical and electronic components of the 3D laser inclinometer system. Additionally, Fig. 11 illustrates that the air temperature did not negatively impact the behavior of the laser devices.

Analysis of the data of the 3D laser inclinometer and atmospheric pressure and temperature gauges (see Fig. 11) shows the following:

– lack of influence of the dynamics of the thermodynamic parameters of the atmosphere on the operation of the lasers of the 3D inclinometer;

– several anomalous phenomena (approximately 3) of significant displacement with non-standard shapes, which are displayed on the graphs of the 3D laser inclinometer from above;

– daily oscillation of temperature which has almost the same amplitude, which is important for confirming the stability of the lasers.

To analyze and identify the primary reasons for the initial significant deviation from its zero position value in relative displacement to this new point, it is optimal to collect data over a specified period from 2024-01-11 13:06:31 to 2024-02-06 23:05:32 (Fig. 12, *b*) plotted on the Google map http://lavra.igs-nas.org.ua/GoogleMaps/TST01/ (Fig. 12, *a*). In the 2D drawing (Fig. 12, *b*) of these data, it can be seen that there are both «soft» oscillations and a significant displacement in the direction of artificial voids on the territory of the closed garden of the KPL.

The analysis of the second significant deviation of the value of the position of the 3D laser inclinometer is carried out for the period 2024-01-21 00:06:44 — 2024-01-28 06:05:20 (Fig. 13, *b*) and plotted on the Google map http://lavra.igs-nas.org.ua/GoogleMaps/TST02/ (Fig. 13, *a*). In the 2D drawing (Fig. 13, *b*) of these data, we can see that there are both «soft» oscillations and a significant displacement in the direction of already two artificial voids with different coordinates on the territory of the closed garden of the KPL.

The analysis of the third group of significant deviations of the position values of the 3D laser inclinometer was carried out for the period 2024-02-10 00:05:02 — 2024-02-24 23:05:14 (Fig. 14, *b*) and plotted on the Google map http://lavra.igs-nas.org.ua/GoogleMaps/TST03/ (Fig. 14, *a*). In the 2D drawing (Fig. 14, *b*) of these data, we can see that in this time interval there are already no «soft» oscillations. Also, a group of significant displacements dominates in the direction of both two different artificial voids formed on the terri-

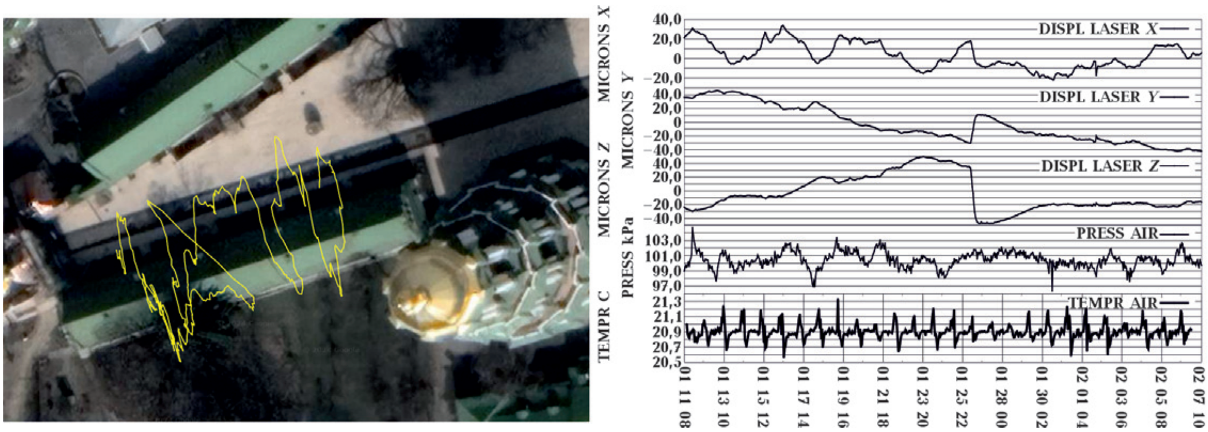


Fig. 12. Daily periodic displacements of the laser 3D inclinometer pendulum from 2024-01-11 13:06:31 to 2024-02-06 23:05:32 and plotted on the photo of building No. 3 on the map http://lavra.igs-nas.org.ua/GoogleMaps/TST01/.

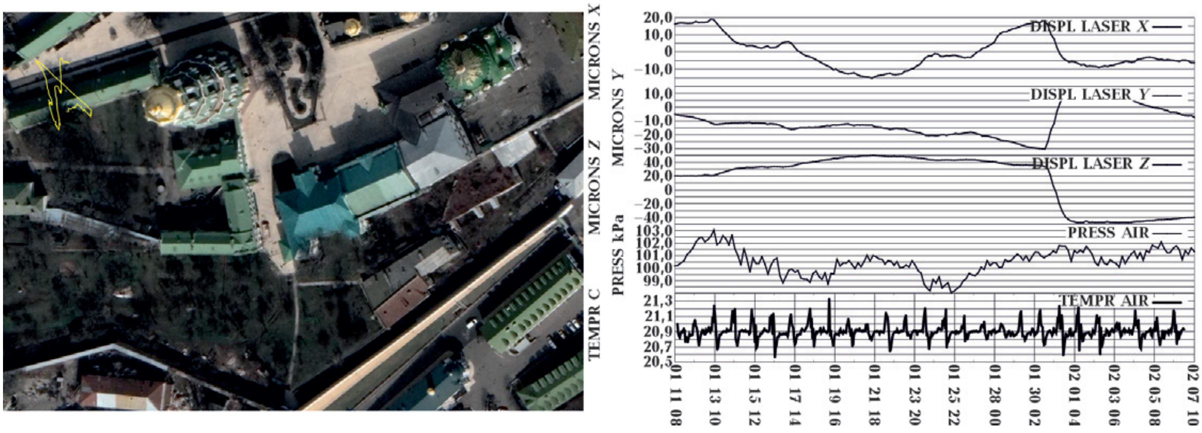


Fig. 13. Daily periodic displacements of the laser 3D inclinometer pendulum from 2024-01-21 00:06:44 to 2024-01-28 06:05:20 and plotted on the photo of building No. 3 on the maphttp://lavra.igs-nas.org.ua/GoogleMaps/TST02/.

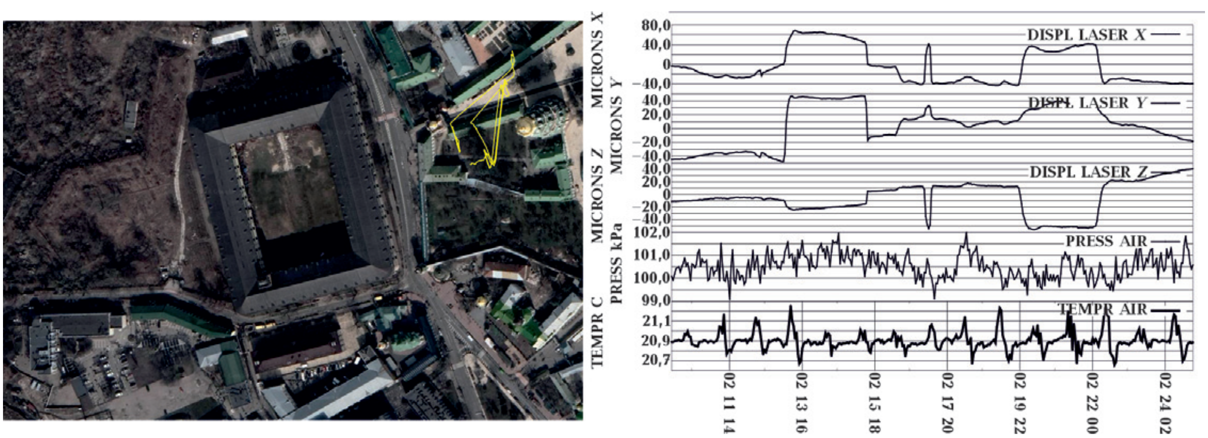


Fig. 14. Daily periodic displacements of the laser 3D inclinometer pendulum from 2024-02-10 00:05:02 to 2024-02-24 23:05:14 plotted on the photo of building No. 3 on the map http://lavra.igs-nas.org.ua/GoogleMaps/TST03/.

tory of the closed garden of the KPL and in a third direction, which is significantly shifted to the left relative to the vertical, presented in Fig. 14, *a*. In addition to long-term displacements, rapid displacement was also discovered. It can have dangerous consequences for the historical structures of the KPL due to the significant speed of its development.

The main task at the moment is finding the causes of such fundamentally dangerous phenomena as significant shifts in the environment with underground caves on the territory of the KPL, where a failure has already occurred in the area where the heating pipeline is located. As we can see, significant displacements occur precisely in the directions of historical failures and voids that had been formed earlier. What exactly causes such destruction of the upper layer on the territory of the KPL? Why do these void zones sometimes become active, and sometimes, not? What affects their level of danger? One of the answers to these questions can be the time of their existence. However, frequent repetitions of groups of these events, such as destructive displacements, are then not possible, because failures from the time of existence can be repeated only after a sufficiently long time — from three to ten years. From 1980 to the present time, the day has increased by approximately 37 seconds, based on the fact that the rotation of our planet is being slowed down due to the influence of the Moon on the Earth's core and crust [Witze, 2016], which also rotate relative to each other because of this also not completely synchronously.

In order to find an answer to these questions, it is optimal to add the results of parallel studies of the influence of the moon's condition on the formation of cracks in building No. 4 of the KPL. To do this, we will consider the position of the Moon during this last period of time of abnormally sharp landslide studies, which is presented in Fig. 15, 16.

In Fig. 16, you can see that the direction and angle of the relative movement of the Moon relative to the observation points in buildings No. 3 and No. 4 does not change and does not depend on the time of the Moon's movement relative to these observation points for any time interval. Unfortunately, such almost constant values of the angles and directions of the Moon's movement relative to these areas of the KPL structures, where cracks are constantly formed, constantly cause their number to increase, because the destruction continues to grow.

Conclusions. The use of seismometers of two different types (a 3D velocimeter, an 1D velocimeter and a 1D microphone) made it possible to record various military-type events (flight of missiles, explosions, the operation of anti-missile anti-aircraft systems, etc.) with infrasound radiation in the frequency range of 10—500 Hz.

The analysis of shows the following:

– the technical parts of laser measurements were not affected by the influence of atmospheric temperature changes on the process of its long-term work in the middle room of the third building from 2024-01-11 13:06:31 to 2024-03-03 12:06:23 (see Fig. 12);

– anomalous sharp displacement is associated with the directions in the area of the

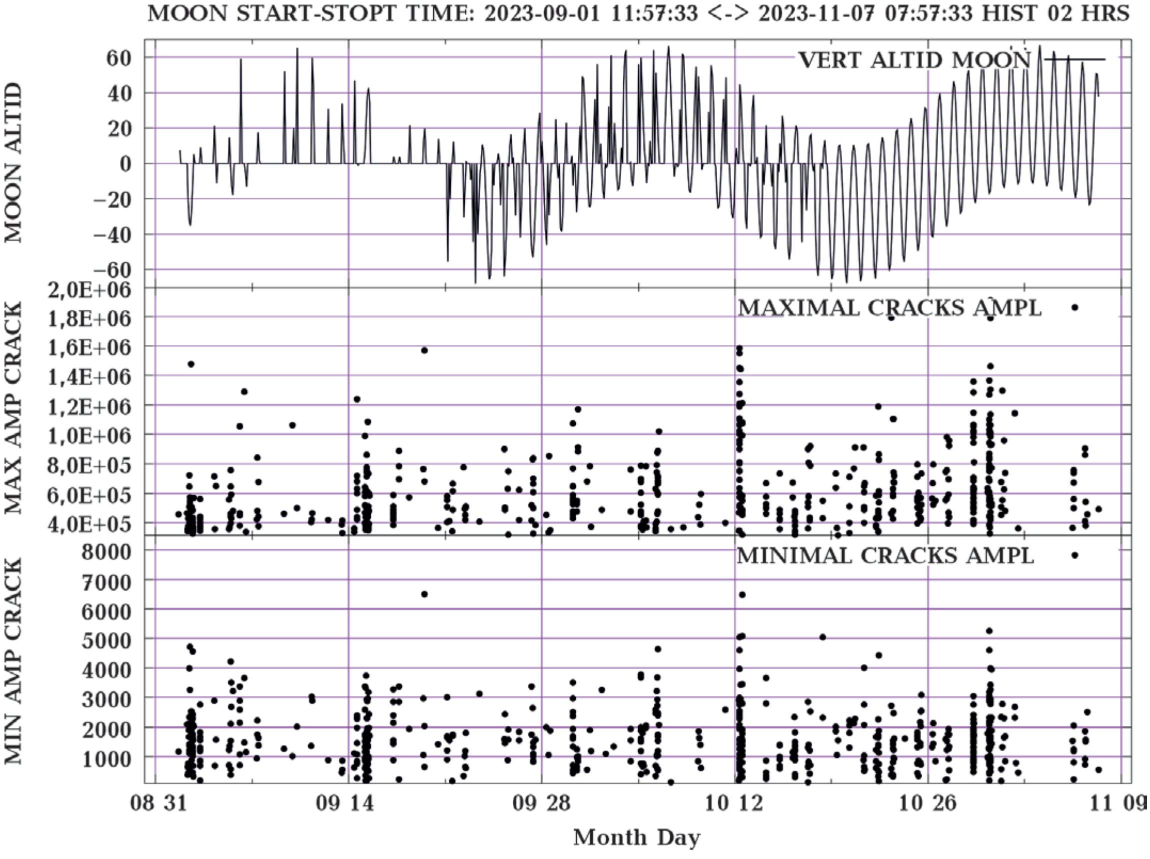


Fig. 15. General view of the implementation of the process of formation of the number of cracks in building No. 4 of the KPL and their minimum (bottom) and maximum (middle) amplitudes for the research period from August to November 2023.

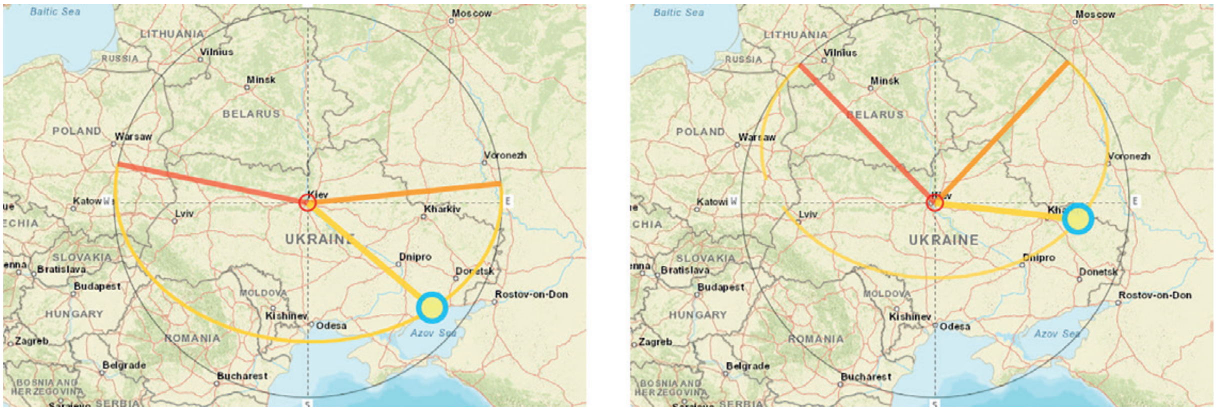


Fig. 16. Trajectories of the Moon's movement for the period from 2024-02-10 00:05:02 to 2024-02-24 23:05:14 relative to the location point of the laser 3D inclinometer on the full-scale map of the country to track its relative position relative to North and South of Ukraine https://www.mooncalc.org/#/50.5187,30.38,5/2024.02.06/23:58/1/3. The Moon trajectory: *a* — 13 February 2024 12:35 UTC+2 (see Fig. 14, *b*); *b* — 18 February 2024 12:35 UTC+2 (see Fig. 7).

closed garden of the KPL near the Belfry, where various technical failures have formed in the areas until now undiscovered underground voids on the territory of the KPL, which are located exactly under the surface of this closed garden of the KPL at a depth of approximately 10—12 meters;

– anomalous sharp displacement is associated with the trajectory of the Moon (see Fig. 15, 16) relative to these voids on the territory of the KPL, because such significant and sharp shifts do not occur in other regions of homogeneously filled regions of the upper part of the KPL environment.

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References

Britsky, O., Shcherbyna, S., Pigulevskiy, P., & Cherevko, I. (2023). A new laser approach for seismic risk assessment. *Visnyk of Taras Shevchenko National University of Kyiv, Geology*, (3), 10—18. http://dx.doi.org/10.17721/1728-2713.102.02.

Chalyi, O., Feshchenko, A., & Shcherbyna, S. (2023). The cause of cracks on the walls of buildings in the Kyiv-Pechersk Lavra. *XVII Int. Sci. Conf. «Monitoring of Geological Processes and Ecological Condition of the Environment» 7—10 November 2023, Kyiv, Ukraine*.

Cherevko, I. (2018). Development of exogenous geological processes in the territory of the

Kyiv-Pechersk Lavra and their impact on the state of monuments. *Sivershchyna in the history of Ukraine*, (*11*), 31—36 (in Ukrainian).

Cherevko, I. (2021). Monitoring the development of dangerous geological processes in the territory of the Kyiv-Pechersk Lavra: experience, problematic issues, solutions. *Sivershchyna in the history of Ukraine*, (14), 39—47 (in Ukrainian).

Kendzera, O.V., Belov, I.D., Shcherbina, S.V., Lisovyi, Yu.V., Ilyenko, V.A., Haydaichuk, V.V., Dedov, O.P., & Cherevko, I.A. (2016). Experimental verification of the calculated vibration model of the Great Bell Tower of the Kyiv-Pechersk Reserve. *Geoinformatika* ,(2), 68—78 (in Ukrainian).

Rybin, V., Sakhno, A., Kutsyba, V., & Cherevko, I., et al. (2001). *Develop methodology and justify monitoring of the geological environment in the historical zones of Kyiv to protect historical and architectural monuments*. Research Report. Kyiv: IGNASU, 168 p. (in Ukrainian).

Witze, A. (2016). Moon's pull can trigger big earthquakes. Geologic strain of tides during full and new moons could increase magnitude of tremors. *Nature*. http://dx.doi.org/10.1038/nature.2016.20551.

Сучасна оцінка ризику впливів природних і воєнно-техногенних факторів на стан історичних споруд Києво-Печерської лаври

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За свою тисячолітню історію Києво-Печерська лавра зазнала чимало бід. У час, коли боротьба з релігією була частиною державної ідеології, собор і монастир були закриті, а їхні безцінні скарби конфісковані. Навіть у бурхливі 1930-ті роки, коли більшовики знищили десятки унікальних храмів і церков у Києві, Успенський собор залишився неушкодженим. Чорні дні для вікової святині настали під час німецької окупації восени 1941 р. Спочатку святиня була розграбована, багато матеріальних і художніх цінностей було вивезено. У листопаді 1941 р. серія вибухів знищила головний храм Києво-Печерської лаври, який слугував усипальницею для київських князів. У лютому 2022 р. у нашій країні знову почалася війна, і представлені в статті сучасні наукові технології дають можливість оцінити вплив військових подій будь-якого рівня небезпеки, які тривають в Україні більше двох років, на стан всіх частин Києво-Печерської лаври, яка є занесеною до списку Світової спадщини ЮНЕСКО.

У статті представлено результати аналізу роботи пристроїв різного призначення — від фіксації сейсмічно-акустичних хвиль, які мають високу частоту власних коливань, до низькочастотних, які фіксуються лазерним інклінометром. Також наведено результати сучасної автоматизованої обробки даних різними методами — від спектрального метода розпізнавання сигналу до метода сучасного автопікера часу визначення вступу хвиль AIC, який дає змогу чітко визначати час вступу вібраційних хвиль різного походження — від утворення тріщин у історичних спорудах Києво-Печерської лаври до вібраційних хвиль технічного і природного походження.

Ключові слова: військові події, вібрація, деформація, велосиметр, лазерні інклінометри.