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STRUCTURAL HEALTH MONITORING OF HERITAGE BUILDINGS UNDER MILITARY ACTIONS

Iryna CHEREVKO[1], Tetiana KRIL[2,*], Vasyl MOSTOVYY[3], Sergiy SHCHERBYNA[4]

[1] National Preserve "Kyiv-Pechersk Lavra," Lavrska Str., Kyiv, 01015, Ukraine; ira071165@yahoo.com
[2] Institute of Geological Sciences of the NAS of Ukraine, Kyiv, Ukraine; kotkotmag@gmail.com
[3] Military Institute of Taras Shevchenko National University of Kyiv, Yulia Zdanovska Str., 81, Kyiv, 03680, Ukraine; vasyl.mostovyy@gmail.com
[4] S. Subbotin Institute of Geophysics of the NAS of Ukraine, Academician Palladin Ave., 32, Kyiv, 03680, Ukraine; nohup@ukr.net

Abstract

In military operations, the historical heritages of the Kyiv-Pechersk Lavra are under the negative influence of dynamic loads. The research aimed to determine the dynamics of the historical building condition under the influence of missile attacks and its reaction to explosions. Based on the data of speed and acceleration measurements with the help of a mathematical apparatus, the response of the building to three military events at different distances from it was determined. Informative parameters of the structure's response are frequencies and logarithmic decrements for each harmonic before, during, and after the explosion. Logarithmic decrements on different harmonics show that the highest values correspond to frequencies (0.4584, 0.4729, 0.4935) that correspond to frequencies 4.31-4.36 Hz, and the lowest (0.1847, 0.2046, 0.2059) correspond to 3.02-3.28 Hz. The inherent frequencies of the K-3 building, dangerous during explosions at distances of 3.2-7.4 km, are set at 2.45-3.68 Hz, as resonance from explosive events can occur on them. Different types of formation and behavior of microcracks in terms of the amplitude in the building were distinguished by the useful signal method of the Akaike Information Criterion auto picker. The recorded cracks result from the influence of natural and anthropogenic factors, including war events.

Keywords*: Historical heritage; Kyiv-Pechersk Lavra; Geological environment; Building stability; Structural health monitoring; Missile attack*

Introduction

The historical and architectural heritage of the National Reserve "Kyiv-Pechersk Lavra" includes more than 144 immovable objects [1]. They were formed, rebuilt, subjected to equal influences over the centuries, and had different levels of technical wear. Their technical condition is under constant control of the Reserve employees. On the Lavra territory, there is a constantly operating monitoring system for changes in groundwater levels, which includes more than 48 hydrogeological wells and three hydrophysical posts; some historical monuments are equipped with geodetic marks and benchmarks to control deformations and the opening of cracks; unstable areas are affected by the development of engineering and geological processes and phenomena; and areas are periodically examined by non-destructive methods of electromyography and natural electric field, etc. [2-4].

* Corresponding author: kotkotmag@gmail.com

From 2023, the assessment of the technical condition of the historical buildings of the Kyiv-Pechersk Lavra is carried out based on modern approaches of Structural Health Monitoring (SHM) with the use of Non-Destructive Techniques, i.e., modern systems of electronic registration, storage, and analysis of data on the condition of building structures using accelerometers, acoustic sensor emissions, GPS sensors, and environmental condition sensors [5].

SHM methods are widely used not only for modern buildings but also for historical buildings [6, 7]. The work [8] presented the application of continuous structural health monitoring (Continuous SHM–CSHM) on two towers and one sculpture of the medieval era in Italy. The study demonstrates the mathematical algorithm for automated operational modal analysis (A-OMA).

Accelerometers are the most common type of sensors used in SHM: capacitive, piezoelectric, based on force balance measurement, and micro-electromechanical (MEMS) devices [6-9].

In particular, in studies [10-12], accelerometers were used to monitor historical buildings to assess their dynamic characteristics under external influences. Some of these studies identified building modal parameters (eigenfrequencies, damping ratios, and mode shapes) to refine numerical models of buildings based on the finite element method. In contrast, others identified damage after hazardous natural phenomena occurred.

The results showed the accurate estimation of modal parameters using only a few sensors and the environment's critical influence on the structure's dynamic properties. Other examples of SHM application to historical buildings are described in [10-14].

Due to military influences, buildings additionally suffer from the spread of vibration waves during missile attacks, shooting down UAVs, etc. Therefore, it is essential to analyze the dynamics of the state of building structures of the historical and cultural heritage of the Kyiv Pechersk Lavra. To study the dynamics of the parameters characterizing the strength parameters of this structure, the concept of seismoacoustic monitoring of natural and building objects was used, in the framework of which the object under investigation is mapped into an n-dimensional vector of the Euclidean space of informative parameters using a physically reasonable parametric model [15].

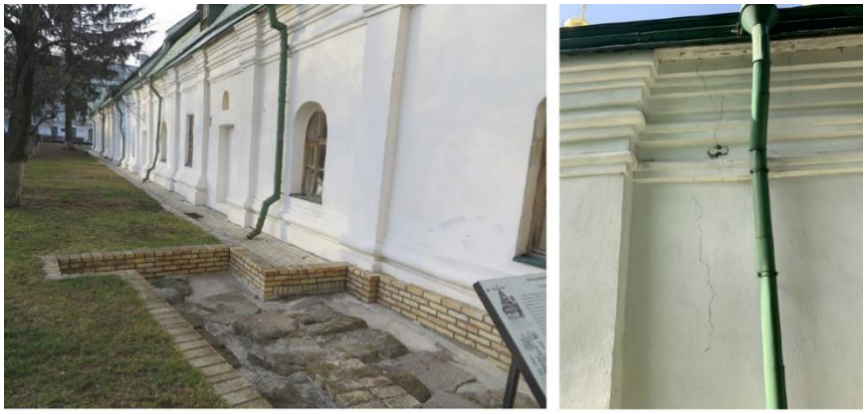
A change in the condition of building structures during their operation can lead to undesirable and sometimes even catastrophic consequences. The cause of the destruction of engineering structures and their components is most often structural changes in composite materials, under which destruction occurs in operational loads and natural deterioration [16].

The monitoring concept was based on the following physical principles. Since the speed of propagation and the form of longitudinal and transverse waves in the material depend on the elastic parameters of these materials, the change in these parameters leads to changes in the spectral characteristics of the emission signals that occur in the material deterioration [15]. Emission refers to the redistribution of energy in the material. The appearance of emitted signals accompanies this. Signal emissions are stress waves generated by a sudden internal redistribution of stress in the material caused by changes in the internal structure, i.e., material fatigue. Emission is caused by the redistribution of energy in the material. The emergence of emitted signals accompanies any redistribution of energy in the material. The superposition of such signals generates an emission field [17, 18].

From the point of view of materials science, fatigue is when local structural damage develops and occurs during cyclic loads on the material [19]. Cyclic stress leads to material fatigue. Fatigue leads to irreversible deformations of the material, that is, to its deterioration. The deterioration process in the proposed models is a change in material parameters reflected in the features' space. Parameterization of the analyzed process takes place using its approximation of a parametric model with free parameters. Thus, the seismoacoustic monitoring of natural and building structures is reduced to regular observations of the free parameters of the selected model [15].

Changes in natural frequencies may indicate changes in the rigidity characteristics of building elements due to accumulated damage. For example, a 5% decrease in natural frequency may indicate the presence of damage [20]. The environment also affects the dynamic parameters of the studied systems [21, 22]. In research [23], for example, an increase in the values of the lowest natural frequencies of a 22-story reinforced concrete building was observed with an increase in temperature within 4–5%.

Among the complex of buildings of the Kyiv-Pechersk Lavra, the K-3 building was chosen for seismoacoustic observations based on the selected unstable and potentially dangerous areas and the established technical condition [24, 25]. According to the technical condition, the cells belong to the I category [26]. Ancient vertical and diagonal structural cracks above the window openings and on the cornice can be observed on the facades of the monument. In the interior, there are numerous vertical and inclined cracks in the walls, destruction of the plaster layer (Fig. 1).



a) b)

Fig. 1. General view of the south facade (a) and the crack on the cornice with geodetic marks (b)

The research aims to determine the dynamics of the condition of the historical K-3 building under the influence of military rocket attacks and its reaction to explosions.

To achieve the goal, the following tasks were completed: collection of materials for engineering and geological conditions of the research area; carrying out a seismoacoustic experiment; mathematical analysis of seismoacoustic monitoring data to identify possible structural damage (changes) of building structures; determination of types of cracks in a historical building.

Materials and Methods

The scheme of engineering protection of the territory (scale 1:1000) [27]; the plan of the current state of the Reserve (scale 1:1000) [28]; data of engineering-geological surveys [29-32]; the geodetic plan (scale 1:500); the map of the Reserve territory in the format *dwg, historical and archaeological materials [33] are used.

Methodology of measurements.

To monitor the technical condition of the structures, electronic instruments (sensors) of the Institute of Geological Sciences of the National Academy of Sciences of Ukraine, manufactured considering the conditions of the territory and structures of the Kyiv-Pechersk Lavra of RODEN LLC [34], were used. A three-component velocimeter and a single-component accelerometer are embedded in the basis of the AS-4 No. 1 four-channel seismic recorder complex. Figure 2 shows the location of the velocimeter and accelerometer. The velocimeter is on the floor, and the accelerometer with the microphone is on the wall next to the crack.

a) b)

Fig. 2. General view of the location of the velocimeter (a) and the accelerometer and microphone (b) in the premises of the K-3 building

The specialized four-channel seismic recorder AS-4 No. 1 provides registration of microseismic and seismic activity of anthropogenic and natural origin, designed for measuring the speed m/s and acceleration (m/s²) of microseismic and seismic vibrations from the surface of the soil, structural elements of buildings and structures, and from other points of manifestation of these events on the territory of the Kyiv-Pechersk Lavra. The power range of measured phenomena includes the formation of new and the behavior of existing microcracks; explosions felt on the territory of the Reserve and around it; other anthropogenic events, etc. A three-channel velocimeter and a single-channel accelerometer with built-in amplifiers of the output signal transmit the registered signals to a block of a four-channel 24-bit analog-to-digital converter with a minicomputer to ensure the operation of the technical primary software. With the international GPS time synchronization system and network data transmission system, Figure 3. Built-in software allows you to save measurement records on an external medium and transfer them over the Internet to the http://lavra.igs-nas.org.ua server for data processing using statistical methods. This will enable you to identify registered geophysical phenomena, determine statistical and spatial characteristics of microseismic and seismic activity in the area of the device, assess the actual level of concentration of dangerous events of various types, determine the level of activity of voids, monitor the level of safety, and issue warning notifications.

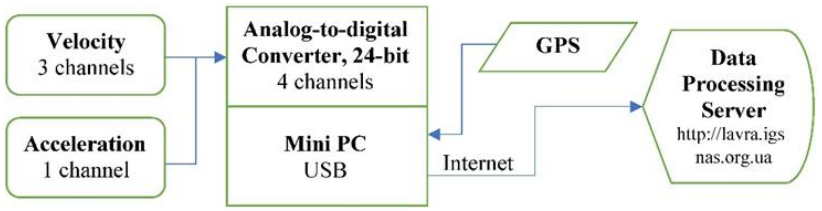


Fig. 3. General block diagram of seismic recorder AS-4 No. 1

Special software allows you to evaluate in numerical terms the actual level of the reserve of stability of the soil massif and historical structures, particularly in the areas of the spread of underground voids, sinkholes, and places of network breaks. According to the results of the initial processing of records in the form of speed and acceleration of microseismic vibrations and explosions, namely, according to their amplitude, frequency, time, and other characteristics, it is possible to identify the types of these phenomena, determine the location zones of possible voids,

determine the assessment of the level of safety/danger of the phenomenon, and determine the stability of structural elements of buildings of historical and architectural significance.

Internal data is stored in GSE (cm6) format on an external USB device. External data storage in MSEED format is implemented inside an external computer or externally to it, such as a 1TB USB. Temporary files are deleted after converting to MSEED. Viewing and analysis of data saved in the MSEED format are performed by the Seis-Gram2K80_SCHOOL.jar Java program on the laptop desktop [35].

Model of optimization of dynamic parameters of monitoring of building structures based on seismoacoustic analysis.

A physically realized signal [36] is well approximated by a superposition of oscillators. For the oscillator model:

$$y(t) = \eta(t)e^{-\alpha t}\sin(\omega t). \quad (1)$$

The following generalization is natural:

$$y(t) = A\eta(\mathrm{t}-\tau)\exp\{-\alpha(t-\tau)\}\sin[\omega(t-\tau)]. \quad (2)$$

Here η(t-τ) is the Heaviside function. [37], for the oscillator pulse that entered at the instant of time τ.

Formulas 1-2 represent an oscillator model in which:

– y(t) – observed data,

– {A, τ, α, ω} – vector of free parameters of the model, where A – oscillation amplitude, τ – signal arrival time, α – is the parameter characterizing signal attenuation (decrement), ω – signal frequency.

The model consists of K submodels and is a superposition of pulses, each of which is given by formula (2) and is included in the model by a vector of physically meaningful free parameters of the oscillator:

$$\boldsymbol{P}_{\langle k\rangle} = \{A_k, \tau_k, \alpha_k, \omega_k\} \quad (3)$$

and the model takes the form:

$$M(t,\mathbf{P}) = \sum_{k=1}^{K} A_k\eta(t-\tau_k)\exp\{-\alpha_k(t-\tau_k)\}\,sin[\omega_k(t-\tau_k)] + n(t), \quad (4)$$

Here $n(t)$ is the additive noise.

In (4), the matrix P. of free parameters of the model is given. The row vector $\boldsymbol{P}_{\langle k\rangle}$ of this matrix completely defines the k-th submodel, and the column vector $\boldsymbol{P}^{\langle s\rangle}$ ⟩ of which represents the related parameters of the submodel. In (5), there are four such associated parameters:

$$\boldsymbol{P} = \{P_{k,s}\},\ k = \overline{1,K},\ s = \overline{1,S}, \quad (5)$$

S – is the number of free parameters in the submodel (the number of columns in the matrix P), K – is the number of submodels (number of rows in the matrix P).

Thus, the rectangular matrix of free parameters P with dimension $K \times S$ of the formula (5) defines the model (4).

If we connect related vectors into a matrix, then:

$$\boldsymbol{P} = \{\boldsymbol{P}^{\langle 1\rangle}, \boldsymbol{P}^{\langle 2\rangle}, \boldsymbol{P}^{\langle 3\rangle}, \boldsymbol{P}^{\langle 4\rangle}\}, \quad (6)$$

In (6), the combined vectors have the form:

$$\boldsymbol{P}^{\langle 1\rangle} = \boldsymbol{A} = \begin{Bmatrix} A_1 \\ \vdots \\ A_k \\ \vdots \\ A_K \end{Bmatrix}; \boldsymbol{P}^{\langle 2\rangle} = \boldsymbol{\tau} = \begin{Bmatrix} \tau_1 \\ \vdots \\ \tau_k \\ \vdots \\ \tau_K \end{Bmatrix}; \boldsymbol{P}^{\langle 3\rangle} = \boldsymbol{\alpha} = \begin{Bmatrix} \alpha_1 \\ \vdots \\ \alpha_k \\ \vdots \\ \alpha_K \end{Bmatrix}; \boldsymbol{P}^{\langle 4\rangle} = \boldsymbol{\omega} = \begin{Bmatrix} \omega_1 \\ \vdots \\ \omega_k \\ \vdots \\ \omega_K \end{Bmatrix}. \quad (7)$$

The model of optimization of dynamic parameters of monitoring of building structures based on seismoacoustic analysis in terms of the matrix of free parameters P takes the form:

$$M(t,\boldsymbol{P}) = \sum_{k=1}^{K} \boldsymbol{P}_k^{\langle 1\rangle}\eta(t-\boldsymbol{P}_k^{\langle 2\rangle})\,exp\{-\boldsymbol{P}_k^{\langle 3\rangle}(t-\boldsymbol{P}_k^{\langle 2\rangle})\}\,sin[\boldsymbol{P}_k^{\langle 4\rangle}(t-\boldsymbol{P}_k^{\langle 2\rangle})], \quad (8)$$

here A, τ, α, ω – are a column vectors consisting of K rows, K – is the number of submodels. The matrix is formed as a combination of vectors (6), $P_{k,s} = P_k^{\langle s\rangle}$. In the model (4) $s = \overline{1,S};\ S = 4$.

The metric $L_2(0,T)$characterizes the energy of the process under investigation. Therefore, it is expedient to construct the criterion (objective function) $Q(\boldsymbol{P})$ in the metric $L_2(0,T)$for model (4) and field observations V(t) on the interval (0, T).

$T = \Delta t \cdot S1$, here – Δt quantum of time, S1 – the number of sampling points on an interval that expressions can represent, V(t) – is the vector of observation data on the interval $T = \Delta t \cdot S1$.

$$Q(\boldsymbol{P}) = \|V_{s1} - M(t_{s1}, \boldsymbol{P})\|_{L_2};\ k = \overline{1,K}. \tag{9}$$

To find the extrema of the function $Q(\boldsymbol{P})$, you need to solve a system of equations concerning all elements of the matrix $\boldsymbol{P}$:

$$\frac{\partial Q(\boldsymbol{P})}{\partial P_{s,k}} = 0,\ k = \overline{1,K}; s = \overline{1,S}. \tag{10}$$

Considering the similarity of related submodels, it is possible to sequentially consider derivatives in the direction of vectors $\boldsymbol{P}^{\langle k\rangle}$, related parameters of different submodels.

$$\frac{\partial Q(\boldsymbol{P})}{\partial \boldsymbol{P}^{\langle k\rangle}} = \begin{Bmatrix} \frac{\partial Q(\boldsymbol{P})}{\partial \boldsymbol{P}_1^{\langle k\rangle}} \\ \cdots \\ \frac{\partial Q(\boldsymbol{P})}{\partial \boldsymbol{P}_S^{\langle k\rangle}} \end{Bmatrix} = \boldsymbol{0} = \begin{Bmatrix} 0 \\ \cdots \\ 0 \end{Bmatrix}. \tag{11}$$

A global minimum must be selected from many local extrema.

Problem (9) is a nonlinear regression problem [38, 39]. To solve this problem, it is necessary to find the global minimum of criterion (9). To do this, we select a set of points in the neighborhood of which we find the local minimum of criterion (9) (in this problem, the set of points was chosen by the Monte Carlo method [40, 41], according to a priori distributions; thus, we get a point in the model parameter space, in the neighborhood of which is a local extremum [42-44], and we look for the minimum of criterion (9) on the set of all local extrema, that is, we choose the smallest one on the set of all local minima. This algorithm ensures the convergence of our problem to the measure.

Thus, we find the global minimum of the functional Q($\boldsymbol{P}_k$) on the set of admissible, with known a priori distribution, vectors Pk from the set $\mathfrak{A}_k$.

$$\min_{\boldsymbol{P}_k}\{Q(\boldsymbol{P}_k)\};\ k = \overline{1,K};\ \boldsymbol{P}_k \in \mathfrak{A}_k$$

The results of calculations for the model of five decaying harmonics are reduced to vectors of dimension four, combining one-dimensional parameters, i.e., a 20-parameter model is considered.

Mathematical model of seismoacoustic monitoring of the assessment of the impact of explosions on the building structure.

To carry out seismo-acoustic monitoring of the building, within the framework of this concept, the mathematical model presented in [15] was used to assess the dynamics of the object's parameters characterizing its strength [45].

The model of the dynamics of the shock wave's impact on the condition of the object under study is considered a superposition of the shock wave and the stationary microseismic background that the object of study will generate after the shock wave's impact.

$$M(t, P, \gamma, \sigma) = M(t, P) + M(t, \gamma) + M(t, \sigma), \tag{12}$$

where P is the matrix of free parameters of the stationary microseismic background, which was generated by the research object before the impact of the shock wave, γ is the matrix of free parameters of the shock wave, and σ is the matrix of free parameters of the stationary microseismic background.

In this paper, we will consider a model in which the matrices P, γ, and σ have the same size.

To solve the problem of assessing the state of the object before and after the impact of the shock wave, the form of the shock wave M(t,γ) itself is not sufficiently informative when studying the response of the structure to one explosion; therefore, in this problem, the model M(t,γ) can be neglected. Thus, model (9) can be represented as:

$$M(t, P, \sigma) = M(t, P) + M(t, \sigma). \tag{13}$$

For the model of the stationary microseismic background recorded on the structural elements of the research object before the impact of the shock wave:

$$t \in (t_{s1_0}, t_{s1_0} + T_p); \tag{14}$$

For the model of the object's response to an explosive (shock) wave:

$$M(t, \boldsymbol{\gamma}) + n(t),\ t \in (t_{s1_1}, t_{s1_1} + T_\gamma). \tag{15}$$

For the model of the stationary microseismic background recorded on the structural elements of the research object after the impact of the shock wave:

$$M(\boldsymbol{\sigma}, t);\ t \in (t_{s1_1}, t_{s1_1} + T_\sigma), \tag{16}$$

here $(t_{s1_0}, t_{s1_0} + T_p)$ – is the prehistory interval of the stationary microseismic background, which was registered at the research object before the impact of the shock wave, $(t_{s1_1}, t_{s1_1} + T_\gamma)$ – is the interval of the impact of the shock wave waves, and $(t_{s1_1}, t_{s1_1} + T_\sigma)$ – is the interval during which the stationary microseismic background, which was registered at the research object before the impact of the shock wave, is considered.

The analysis is carried out at the following intervals:

1. At $t \in (t_{s1_0}, t_{s1_1})$ the parameters of the stationary microseismic background, which was recorded on the research object before the impact of the shock wave, are estimated by the background history up to the moment t_{s1_1}, that is, we find the values of the elements of the matrix $\boldsymbol{P}$ (the optimal estimate of $\widehat{\boldsymbol{P}}$ by background history (t_{s1_0}, t_{s1_1})).

2. At $t \in (t_{s1_1}, t_{s1_1} + T_\gamma)$, we estimate the parameters of the "pure" shock wave; that is, we find the values of the elements of the matrix $\boldsymbol{\gamma}$ (the optimal estimate of $\widehat{\boldsymbol{\gamma}}$ on the interval $t \in (t_{s1_1}, t_{s1_1} + T_\gamma)$.

3. On the interval $\left(t_{s1_1} + T_\gamma, t_{s1_1} + T_\sigma\right)$ we estimate the parameters of the stationary microseismic background, which was registered at the research object after the impact of the shock wave, that is, we find the values of the elements of the matrix $\boldsymbol{\sigma}$ (optimal estimate of $\widehat{\boldsymbol{\sigma}}$ according to the history $((t_{s1_0}, t_{s1_1}))$.

4. An assessment of the dynamics of the free parameters of the model (9) before and after the action of the shock wave is carried out within the framework of the selected criterion, for example, $\left\|M(\widehat{\boldsymbol{P}}, t) - M(\widehat{\boldsymbol{\sigma}}, t)\right\|$ in the selected metric, for example, $L_2(0, T)$ i.e. $\left\|M(\widehat{\boldsymbol{P}}, t) - M(\widehat{\boldsymbol{\sigma}}, t)\right\|_{L_2(0,T)}$. Here, T is the interval length during which a comparative assessment of the model parameters is carried out before and after the shock wave's impact.

5. If $\left\|M(\widehat{\boldsymbol{P}}, t) - M(\widehat{\boldsymbol{\sigma}}, t)\right\|_{L_2(0,T)} < \varepsilon$, then we consider that the object is in a stationary state. Otherwise, a decision is made that the object is in a critical state. Here, the value of the threshold ε is chosen subjectively, individually in each task, taking into account both the specificity of the object and the attitude of researchers to errors of two kinds when making a decision, namely "missing the target" and "false alarm."

Main Results

Principal characteristics of the study area and building construction K-3

The research object is located in the Cathedral Square of the territory of the Upper Lavra within the limits of the loess plateau. Absolute marks–188-189 m. The corpus of cells is surrounded by historical buildings: Great Lavra bell tower K-81, Nadbramna church K-27, housings of K-4 cells, etc.

Figure 4 shows a geological cross-section, as a whole, inherent in the engineering and geological conditions of the Upper Lavra. The soil base of the Verkhnaya Lavra monuments is loess-like sandy loam and loam, which are characterized by a significant content of dusty particles (42–83%), considerable porosity (0.3–0.48), and the presence of calcium carbonate cementing inclusions. Loess-like sandy loams belong to the 1st type in terms of subsidence. In the dry state,

they have high values of the angle of internal friction (20–29°), cohesion (0.002–0.039MPa), and deformation modulus (5–20MPa). After water saturation, they decrease significantly: 12–15°, 0.0024–0.0029MPa, and 3–17MPa, respectively [46, 47]. The first groundwater levels from the surface lie mainly 0.5–4.0m below the base of loess subsidence (1st type) soils.

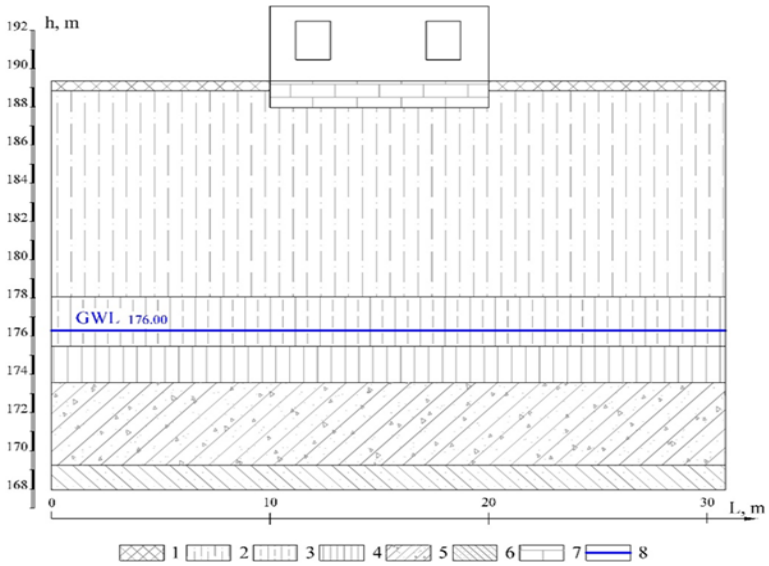


Fig. 4. Geological cross-section along line I-I (see Figure 5): 1 – anthropogenic deposits (tH) – loam light / heavy dusty, sandy dark gray, dark brown, brownish brown, humus in places, with inclusions up to 10–50% construction waste, semi-solid, soft plastic; 2 – eluvial, eolian-diluvial deposits (e,dvP_{III}–H) – dusty, loess, pale-gray, gray-yellow, hard to plastic sandy loam; 3 – eluvial, eoli-an-diluvial deposits (e,dvP_{III}–H) – dusty loam, yellowish-gray, with thread-like veins of carbonates, iron-bearing, soft-plastic; 4 – eluvial, eolian-diluvial deposits (e,dvP_{III}–H) – dusty, brownish-gray, soft-plastic loam; 5 – moraine deposits (gP_{II}dn) – reddish-brown loam with thin layers of sandy loam and brown-gray sand, rigid plastic; 6 – moraine deposits (gP_{II}dn) – light brownish-gray loam, with interlayers of sandy loam and sand, soft-plastic, rigid-plastic; 6 – foundations of building K-3; 7 – groundwater level

The reaction of loess soil types to dynamic loads depends on even slight changes in humidity. These systems can show both positive and negative dilatancy at different humidity values, accompanied by rarefaction at a humidity level above the critical one. Weakly cohesive soils are characterized by the most pronounced selective sensitivity to dynamic loads of individual frequencies ranging from 15 to 45Hz.

The K-3 building is an architectural monument of national importance called "Cells," security number 260088/4, built in the 20s of the 18th century on the site of earlier scattered houses (cells) after the great fire in the Lavra in 1718. It is a one-story brick building with a high gabled roof with a fold, the ends of which are closed with two-tiered, baroque-shaped gables. Plan dimensions are 62×10m. The planning structure of the building is sectional, consisting of five sections divided into groups of rooms (Fig. 5). Each group has a separate exit to the main—northern—facade; the original doorways are bricked up on the south side. The foundations, lying at a depth of up to 1.4m, are brick and strip and are reinforced with reinforced concrete brackets, at the base of which are built granite boulders on a lime solution.

The building was heavily damaged during the Second World War and was left without a roof. During the repair and restoration works of the 1950s, the southern and northern walls were tightened with metal ties throughout the entire volume (every 4-6m). From 2007 to 2010, complex repair and restoration works were performed, including strengthening of strip foundations, strengthening walls by using ties and injecting cracks, restoration of facades, replacement of carpentry fillings, and finishing works in the attraction's interior. In 2013, due to an emergency

leak from the water main, there was an uneven settlement of the foundation soils and the formation of vertical and oblique cracks in the southwestern part of the building.

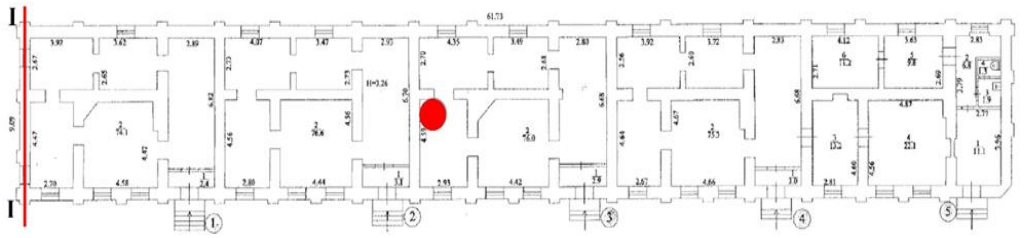


Fig. 5. Scheme of building C-3, red circle - equipment placement point

Seismoacoustic monitoring of the K-3 building construction.

The analysis of the condition of the K-3 building, performed based on seismoacoustic monitoring, is as follows:

1) Creation of a parametric mathematical model of the dynamics of the state of the construction structure of the K-3 building, taking into account the specifics of this object in the form of a superposition of "oscillators" (fading harmonics), characterized by the corresponding "informative parameters" (frequencies, "Q-factor") with the use of mathematical apparatus (see point 2.2).

The quality of the material characterizes the effect of oscillations at a certain frequency and is evaluated.

$$Q = \pi \cdot \alpha$$

Here α is damping parameter in the model (4)

2) Obtained and compared spectral characteristics of experimental accelerograms of the object under study (K-3 building) before, during, and after the explosive event.

3) Compare the informative parameters of the object's oscillation models before and after the explosive event.

Such a comparison makes it possible to draw an indirect conclusion about the presence or absence of structural damage (changes) to the object, which (if present) can be reflected in a change in the relevant, informative parameters of the spectral model of the oscillatory behavior of the object [15, 45].

To assess the reaction of the state dynamics of the construction structure of the K-3 building to rocket explosions in Kyiv, a mathematical model (12) was applied. Since the vectors of the parameters of the signal input and its amplitude are necessary for solving the model (12) but are not informative for assessing the dynamics of the state of the research object, then we focus on the vectors of the object's natural frequencies at the registration point and its logarithmic decrement on these harmonics, which are informative from the point of view of assessing the dynamics of the state of the research object.

This model makes it possible to evaluate the dynamics of the characteristics of the K-3 building (Cells) obtained during the processing of seismic data (accelerograms), which are in the area of the seismo-acoustic frequency range.

Three military events were analyzed – the repulsion of missile attacks that took place in the city of Kyiv: December 29, 2023 – Podilskyi District, Novokonstntynivska St., January 2, 2024, Dniprovskyi District, Rusanivska Channel, January 23, 2024, Solomyanskyi District Stadionna St., Figure 6. Military events took place at different distances from the K-3 building.

Fragments of the recording of accelerograms of the reaction of building structures of the K-3 building are presented in Figure 7.

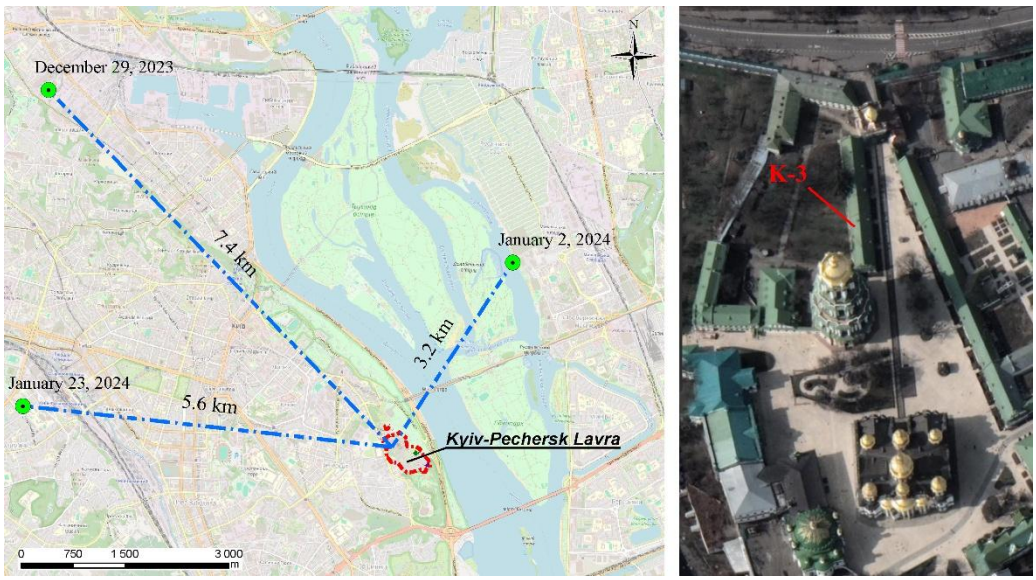


Fig. 6. Places of military events – green circles on the territory of Kyiv (a), the location of the K-3 building in the ensemble of historical objects of the Upper Lavra (b) – photo Google Maps

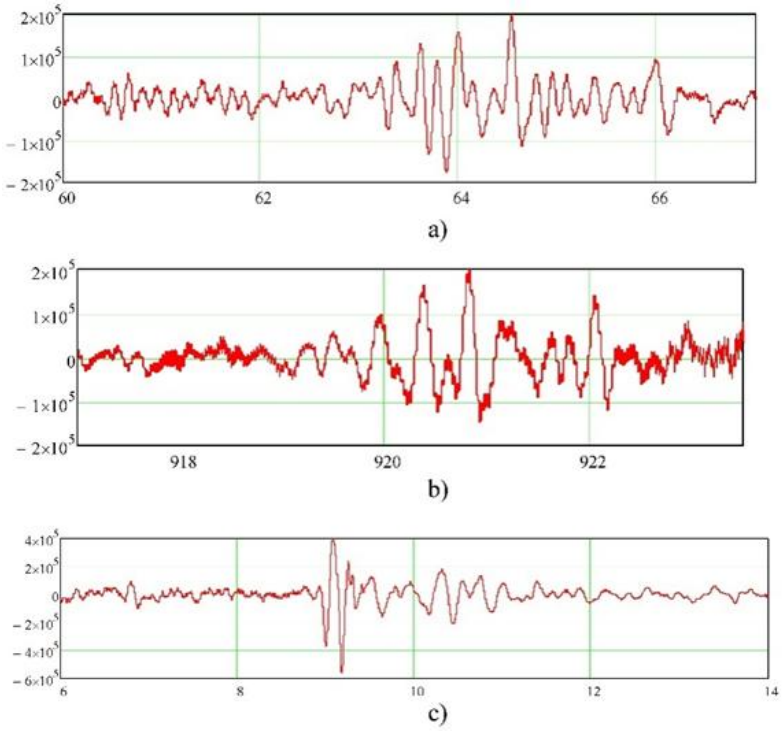


Fig. 7. Fragments of the recording of the accelerogram of the reaction of the building structure of the K-3 building to the explosions of the events on December 29, 2023 (a), January 2, 2024 (b), and January 23, 2024 (c), respectively, against the background noise. The abscissa represents time in seconds; the ordinate represents the amplitude of the oscillation speed in relative units

Informative parameters that characterize the response of the K-3 building to the three military events are given in Tables 1-3, which consist of five sub-models of the oscillator, namely the frequencies and logarithmic decrements of each harmonic before the explosion, during the explosion, and after the explosion.

Table 1. Informative parameters of the accelerogram model of the response of the building structure to the event of December 29, 2023

	Harmonic frequency, Hz	Logarithmic decrement of the harmonic	Harmonic frequency, Hz	Logarithmic decrement of the harmonic	Harmonic frequency, Hz	Logarithmic decrement of the harmonic
	Before the explosion, M(t, P)		The explosion, M(t, γ)		After the explosion, M(t, σ)	
1.	0.7253	0.3537	0.7251	0.3351	0.7572	0.3372
2.	3.3475	0.2057	3.2437	0.1847	3.4732	0.2021
3.	5.6247	0.2642	5.1374	0.2328	5.6347	0.3071
4.	2.5370	0.3751	2.1853	0.3593	2.5291	0.4036
5.	4.2054	0.5274	4.3572	0.4792	4.2736	0.4275

Table 2. Informative parameters of the accelerogram model of the building structure's response to the January 2, 2024, event

	Harmonic frequency, Hz	Logarithmic decrement of the harmonic	Harmonic frequency, Hz	Logarithmic decrement of the harmonic	Harmonic frequency, Hz	Logarithmic decrement of the harmonic
	Before the explosion, M(t, P)		The explosion, M(t, γ)		After the explosion, M(t, σ)	
1.	0.7825	0.3493	0.7529	0.3542	0.7354	0.3403
2.	3.3672	0.2275	3.2759	0.2059	3.4651	0.2257
3.	5.5386	0.2839	5.1358	0.2781	5.6524	0.3241
4.	2.5642	0.3923	2.2374	0.3758	2.5358	0.4352
5.	4.1752	0.5437	4.3276	0.4935	4.2674	0.4273

Table 3. Informative parameters of the accelerogram model of the response of the building structure to the event of January 23, 2024

	Harmonic frequency, Hz	Logarithmic decrement of the harmonic	Harmonic frequency, Hz	Logarithmic decrement of the harmonic	Harmonic frequency, Hz	Logarithmic decrement of the harmonic
	Before the explosion, M(t, P)		The explosion, M(t, γ)		After the explosion, M(t, σ)	
1.	0.7425	0.3205	0.7153	0.3293	0.7378	0.3275
2.	3.2757	0.2183	3.0243	0.2046	3.2572	0.2203
3.	5.5944	0.2835	5.2465	0.2462	5.5359	0.2759
4.	2.4982	0.3907	2.2187	0.3726	2.4845	0.3974
5.	4.3571	0.4972	4.3056	0.4584	4.3552	0.49027

To assess the dynamics of the state of the K-3 in response to all events, the logarithmic decrement before the event on December 29, 2023, and after the event on January 23, 2024, that is, the value before the first explosion and after the third, was estimated. It can be seen that the value of the vectors of free parameters fluctuates within the dynamics of measurements. From this, we can conclude that the dynamics of the K-3 building structures have not changed.

These military events took place at different distances from the object of research: 7.4, 5.6, and 3.2km, but the decrements of the second event are higher than the others. Such a discrepancy is likely related to the different explosive power of the events. Graphs of logarithmic decrements in Figure 8 on different harmonics show that the highest values (0.4584, 0.4729, 0.4935) correspond to frequencies of 4.31-4.36Hz, the lowest (0.1847, 0.2046, 0.2059) to 3.02-3.28Hz.

The logarithmic decrement of oscillations characterizes an elastic system's damping rate of free oscillations. It is a function of the material's properties, the structure's shape, and the features of its interaction with environmental elements.

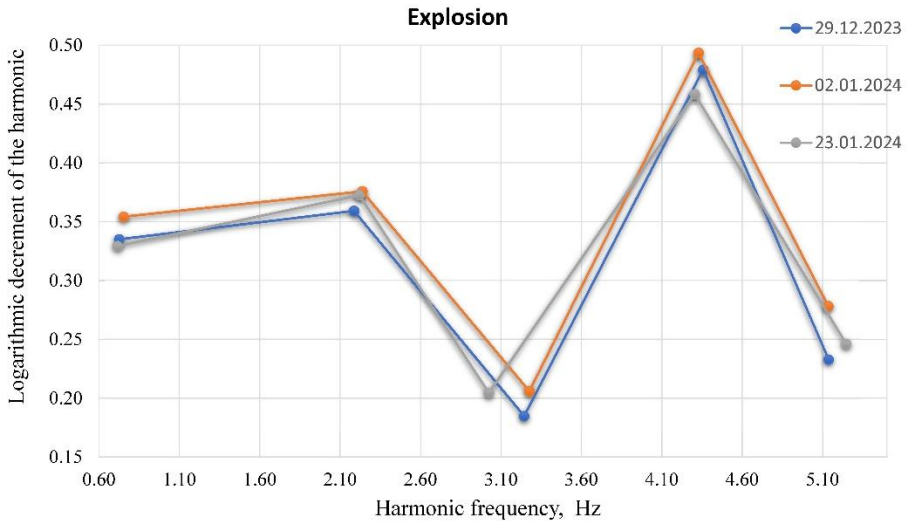


Fig. 8. Logarithmic decrement of the harmonic during explosions

Low values of the decrement under dynamic loading lead to high values of the dynamic coefficient [48, 49] and, respectively, to a more substantial influence of dynamic effects on the parameters of the stress-strain state of the load-bearing elements of the structures of the K-3 building.

Thus, at frequencies of 3.02-3.28Hz, the K-3 building will be subjected to a more substantial dynamic impact and, to ensure safe operation, requires specific constructive solutions to change the mass of the building.

The spectral characteristics of the K-3 building in its undisturbed state were determined. 22 natural harmonics in the range from 0.25 to 29.18Hz are identified. Other natural frequencies have significantly smaller values, and their values can be neglected.

Taking into account that among the natural frequencies, there are values of 2.5417, 3.3721, and 3.6760Hz, which are close to frequencies with a low decrement (3.02-3.28Hz), probably a resonance phenomenon occurred at these values, which led to a long-term oscillatory process, as shown by the attenuation decrement.

The natural frequencies of the K-3 building in the range of 2.45-3.68Hz are dangerous for explosive events at distances of 3.2-7.4km, which, according to our observations, are frequent cases of military influences within the city about the position of the Reserve.

Automatic selection of a useful signal of the "micro-crack" type based on the data of the accelerometer sensor

The analysis of technical tests of various variants of autopickers showed that the most effective method of automatic selection of a useful signal of the "microcrack" type is the Japanese Akaike Information Criterion (AIC) method [50-52]. AIC is an estimator of prediction error and, thereby, the relative quality of statistical models for a given data set [53-55].

The method of automated collection of various data from cracks for the following statistical analysis is built based on a particular MySQL database, which allows statistical processing of various crack parameters accumulated during observations in this database. With its use, you can choose different types of cracks by amplitude and onset time, build histograms of their values at various time intervals, by the minimum and maximum value of their amplitudes, by the ratio of time intervals to their maximum or minimum amplitudes, etc.

Conducted research on testing this approach on data streams with cracks from a 24-bit ADC with two channels of the AS-4 accelerometer No. 1 and a microphone in the C-3 housing of the Kyiv-Pechersk Lavra showed that the AIC method is more effective for detecting a useful

signal of the type "microcrack" than the classic Long Time Amplitude/Short Time Amplitude method (LTA/STA), Figure 9.

The automation of the crack detection process in the K-3 building based on the use of the AIC auto picker made it possible to identify and classify different types of cracks:

- weak, with an amplitude against the background of noise from 0.5 to 1.0 (Fig. 9a);
- medium, with an amplitude that does not exceed the level of 0.3 in the area of normalized AIC values from 0.0 to 1.0 (Fig. 9d);
- strong, which have a normalized amplitude from 0.05 to 1.0 in the range of AIC values (Fig. 9b);
- doubles of different classification types (Fig. 9c and d) - weak doubles, medium doubles, strong doubles, or other combinations thereof - weak and robust doubles, etc.

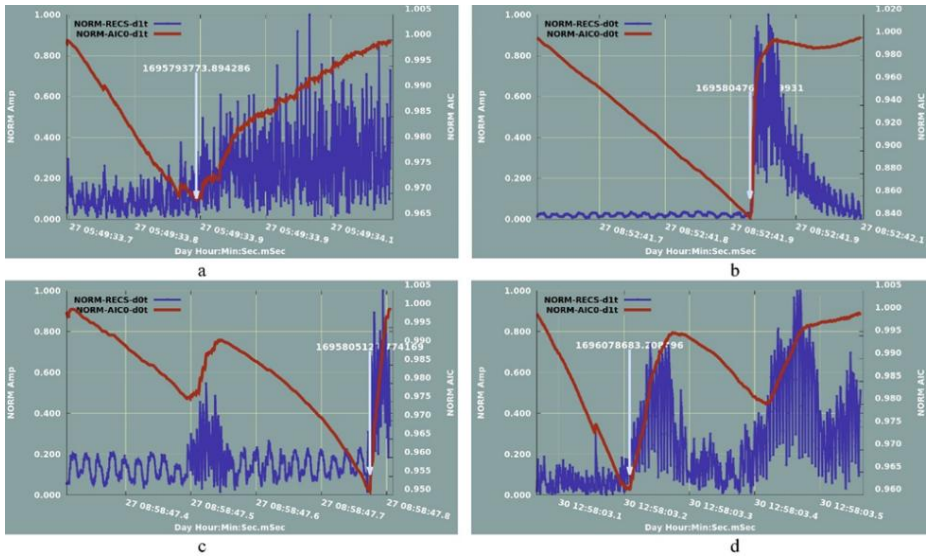


Fig. 9. Identification of different types of microcracks by amplitude (blue graph) in the K-3 building using the AIC auto picker useful signal method (red graph): a – weak slow; b – strong instantaneous; c – weak sharp and medium sharp; d – weak slow

In addition, the unique analysis of the AIC auto picker by the shape of the growth of its values allows you to determine the nature of signals of various types - slow, sharp, or instantaneous, which have the form of a sharp increase of the first signal entry with a duration of up to 0.01sec. (Fig. 9).

The recorded cracks result from the influence of both natural and man-made factors. The intensity of the manifestation of microcracks as a result of natural factors is caused primarily by the subsidence properties of loess loams, slight overwetting of which leads to activation of structural deformations.

The influence of temperature and relative air humidity leads to changes in the physical properties of construction materials. Damage in monitoring geodetic marks on the walls, made of brick on a lime-sand mortar, correlates with seasonal changes, becoming more active in autumn.

Comparing the periods of crack activation with the lunar and solar cycles shows a clear relationship between the deformations of the structures and the initial phases of the moon.

Anthropogenic factors, such as accidents on water supply networks, leading to changes in the stress-strain state of soil foundations and the spread of explosive waves depending on the distance and mass of the explosive substance, have a chaotic, random nature. Still, their influence is reflected in the condition of structures.

Discussion

The issue of the percentage contribution of natural (seismicity, changes in temperature and atmospheric pressure, activation of subsidence, soil shifts, etc.) and anthropogenic (traffic, emergency sources from water supply networks, military events, etc.) factors to the crack resistance of a structure is debatable. Unlike anthropogenic factors, which randomly impact nature, periodic correlations are distinguished among natural factors - annual, seasonal, monthly, etc. The elongation of the building in plan (aspect ratio 1:6) and the absence of expansion joints are design factors that determine the properties of the building for dynamic loads. In this case, they form the structure's low elastic and strength properties with their corresponding spatial orientation to the explosion site.

Conclusion

Based on the data of speed and acceleration measurements, with the help of a mathematical apparatus, the reaction of a building of historical and architectural importance to three military events – the shooting down of missiles at different distances from it – was established. Informative parameters of the structure's response are frequencies and logarithmic decrements for each harmonic: before, during, and after the explosion. Logarithmic decrements on various harmonics show that their highest values (0.4584, 0.4729, 0.4935) correspond to frequencies of 4.31-4.36Hz, and the lowest (0.1847, 0.2046, 0.2059) – 3.02-3.28Hz. The latter is dangerous due to the high values of the dynamic coefficient.

Based on observations of the frequency of shelling of the city, it was established that the most frequent military influences about the position of the Reserve occur within a radius of 7.0-11.0km but are most noticeable on the structural elements of the monuments (by the rattling of window glass, the vibration of window frames, etc.) at a distance of 3.0-4.5km. Moreover, at a distance of 3.2-7.4km, the impact of the acoustic component of the blast wave is minimal, and mechanical vibration is transmitted through the soil foundations. However, in each case, the type of military attack and the mass of explosives (40-500 kilotons) should be considered.

This technique made it possible to identify the natural frequencies of the K-3 building, which are dangerous during explosions at a distance of 3.2-7.4km, which are 2.45-3.68Hz because they can cause resonance from explosive events.

To avoid resonance phenomena and preserve the condition of the historical building, it is necessary to change the range of its frequencies. This is achieved by changes in the structure's stiffness or mass. Adding stiffness increases the natural frequency, and adding mass decreases it. Appropriate calculations should confirm the choice of measures.

Peculiarities of the geological structure, such as the presence of a layer of loess-like loam with a thickness of 12m, create additional threats of changes in the dynamic parameters of the soil during overwetting, for example, by emergency leaks, and may also affect the manifestation of resonance phenomena.

Different types of formation and behavior of microcracks in terms of the amplitude in the K-3 building were distinguished by the useful signal method of the Akaike Information Criterion auto picker. The recorded cracks result from the influence of natural and man-made factors, including and from war events.

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