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O. M. Trofymchuk[1], Iu. I. Kaliukh[1✉], Ya. O. Berchun[1], M. G. Marienkov[2],
B. O. Khymenko[2], V. A. Tytarenko[3], V. V. Vapnichna[4]

A HYBRID NUMERICAL METHOD FOR EVALUATING THE BUILDING SEISMIC PROTECTION BASED ON DIGITAL TWINS

The results of numerical and experimental studies of the residential building vibration and its seismic protection by means of rubber isolators made in Ukraine from a natural rubber are presented. The numerical studies of vertical oscillations of a building with rubber supports at the level of a reinforced concrete grid were performed with the use of the dynamic digital twins developed on the basis of the finite element method. The numerical studies of the digital twins vibrations were performed using the records of soil vibration accelerations obtained under the railway trains effects, as well as for the effects determined by the earthquakes accelerograms. The calculations of buildings on seismic supports with an allowance for seismic loads were performed with determining the factors of safety against overturning for a residential building. The paper shows that the solution to the problem on vibration and seismic protection of buildings is possible when using rubber elements as isolators, which have a nonlinear dependence of stiffness on the load.

Key words: *hybrid numerical method, digital twins, dynamic and non-destructive surveys, rubber isolators, vibration-isolated grid, Vrancea earthquake zone.*

Introduction. The feature of the buildings construction near the railway is that the construction site design can seismicity reach 7 points according to the scales of seismic intensity. For the buildings protection against seismic impacts, the seismic supports stiffness in the vertical direction should be significantly greater compared to the horizontal one. The stiffness estimation is based on the analysis of the enforced vibrations of buildings and structures as multi-mass systems, which are modeled using the equations of motion. The equations of motion are obtained using the D'Alembert and Hamilton principles or Lagrange equations (see, e.g., [17, 28]). The dynamics of systems with multiple degrees of freedom and the application of possible displacements principles and Hamilton's principle for obtaining the equations of motion for the linear and nonlinear dissipative systems are considered in [1, 6, 12, 25]. In [9, 29], the results on the experimental and theoretical evaluation of the railway transport dynamic effects on soil, foundations, and building structures are discussed.

The methods for the analysis of buildings and structures response to seismic effects are presented in [7, 8, 11, 14, 16, 17, 22–24, 26–28, 30–34]. The seismic supports structures, methods for their parameters calculating and application for the buildings seismic protection systems designing are listed in [10, 18, 23].

This work is devoted to the modeling of the "Pid Dubom" residential complex (PDRC) response (Fig. 1) to the railway transport dynamic effects in the Vrancea earthquake-prone zone with the digital twins and the Internet of Things (IoT) application. The residential complex construction site in the city of Lviv is located near the railway track. Before starting the design of the PDRC buildings, it was experimentally determined that the vibration levels of the floors in the buildings residential premises exceeded the values permissible according to the sanitary standards for the dynamic effects of passenger and freight trains. First of all, the trains dynamic effects cause the increased (close to resonant) vertical vibrations of the floors in the buildings located along the railway track. To protect the residential buildings against the vertical and horizontal vibrations propagating through the ground, a vibro-

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✉ kalyukh2002@gmail.com

isolation should be arranged at the foundation level using rubber vibration supports. The effectiveness of the building floors vibro-isolation shall be ensured by the 3–4 range ratio of the frequency of forced impacts from trains and the own vibrations frequency of the building on vibration supports. This condition is ensured when using vibration supports, which are made of low-modulus rubber based on natural rubber.

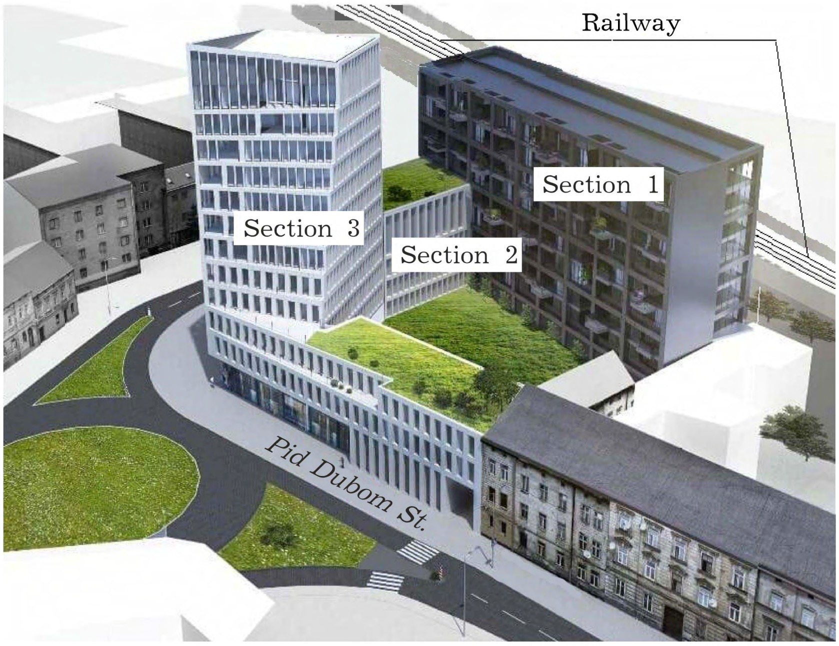

Fig. 1. The situation plan of the construction site for the residential complex at 26 Pid Dubom St. (PDRC) in the city of Lviv.

According to the Eurocode 8 recommendations [5], when designing an earthquake protection system with layered rubber-metal seismic supports, it is necessary to accept the seismic isolators vertical stiffness by 150 times higher than the horizontal one. The vertical vibrations period for a building on seismic supports should be no more than 0.1 s. However, such a requirement does not ensure protecting against the railway transport dynamic effects. For the effective vibration protection of buildings against the railway influences, the vertical vibrations period exceeding 0.2 s should be accepted for the buildings on vibration supports. This problem solution is achieved by the usage of the rubber isolators with the vertical stiffness exceeding the horizontal one by no more than 5–7 times. According to the results of the rubber isolators tests conducted in Ukraine, it is found that the proposed rubber isolators meet the foregoing requirement as to the vertical and horizontal stiffness ratio.

The seismic and vibration protection method proposed and patented in Ukraine [10] is intended both to increase the building structures seismic resistance and to provide for the comfortable living conditions in buildings located near the railway tracks. The protection system with rubber isolators ensures a reduction of seismic loads on the building structures by 1.5 to 2 times. The seismic protection use is governed by the European and national standards EN 1998 1:2004 Eurocode 8 [5] and DBN V.1.1-12:2014 (State Building Normative) [3].

The objective of this study is to justify by means of digital twins and IoT the rubber isolators use for the protection against both the railway transport dynamic effects and the seismic loads.

During the stress-strain state mathematical modeling for PDRC (Fig. 1), several types of difficulties were encountered.

At the initial stage a digital twin, i. e., a digital model was constructed taking into account the changes made during the building complex construction in comparison with the original project including the structural elements replacements, the actual grade of concrete used during the complex renovation (for instance, during the non-destructive testing of a building partially destroyed as a result of a rocket strike at 6-A Lobanovskyi Avenue in Kyiv [15], some discrepancies were found between the design and actual grades of its structural elements concrete), real physical and mechanical properties of building materials, soils real properties, final geometric dimensions of buildings etc. Those problems required the detailed on-site surveys of the complex at 26 Pid Dubom St. with the use of the geometrical analysis, non-destructive tests and other methods. All the works were carried out by the co-authors of the paper during the buildings complex construction and after its completion and commissioning.

The results of those experimental studies directly affect both the correctness of the initial boundary conditions determination and the correctness of the complex finite element model.

The boundary conditions, in addition to the complex geometric characteristics, include the physical and mechanical characteristics of all complex structural elements. The initial conditions include the accelerograms (which take into account the construction site real seismicity at the complex location in Vrancea area and the dynamic effects due to the trains and vehicles movement) experimentally obtained for the direct dynamic calculation of the complex digital twin. Therefore, in addition to the mathematical modeling, the field studies of the soil and buildings floors vibration in the Pid Dubom residential complex built at a distance of 20–30 m from the Kyiv–Lviv railway track should be considered in the paper. Such tasks usually arise when the buildings are erected on the construction sites located in the earthquake-prone zones near the railway tracks. Here, the construction site seismicity is 7 points according to the European and Ukrainian scales of seismic intensity [3].

As a result, for modeling the stress-strain state of buildings and structures subject to dynamic effects, it is necessary to develop such hybrid systems, which would allow research using IoT. To study the strength and vibration characteristics of the complex buildings and soil base, in addition to the traditional packages of LIRA 9.4 or SCAD application software, the IoT systems of sensors for non-destructive testing are necessary. Such IoT system is combined into one information network by means of the cloud technologies and allows obtaining in online mode the information necessary for revealing the particular buildings features. This is the second stage of the digital twin construction for PDRC.

1. The equation of motion for a building flat model under dynamic effects. The study of the gradual and angular vibrations of the multi-mass nonlinear dynamic models with seismic protection systems is performed using the step-by-step integration of differential nonlinear equations (direct dynamic method) for the specified accelerograms (kinematic impact at the building base during earthquakes). The numerical studies of the forced vibrations in the "pile base-seismic supports-foundation-building" system under seismic effects determined by the accelerograms at the building base level were carried out using the multi-mass flat (Fig. 2) calculation dynamic models (CDM).

Considering the damping according to the Voigt hypothesis and dry friction forces at the foundation level, the forced vibrations differential equations in a matrix form for a building flat multi-mass CDM are obtained in the following form:

$$\mathbf{M}\ddot{\mathbf{x}}(t)+\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{K}(\mathbf{x})\mathbf{x}(t)+\mathbf{H}\,\mathrm{sgn}(\mathbf{x}(t))=-\mathbf{M}\ddot{\mathbf{x}}_0(t)\,. \qquad (1)$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}(\mathbf{x})$, and $\mathbf{H}$ are the matrices of the system masses and moments of inertia, damping, nonlinear stiffness and dry friction forces, respectively; $\ddot{\mathbf{x}}(t)$, $\dot{\mathbf{x}}(t)$, $\mathbf{x}(t)$ are the vectors of acceleration, velocity, and displacement of the building foundation and storeys floors; $\ddot{\mathbf{x}}_0(t)$ is the soil acceleration vector (the accelerogrames recorded during an earthquake or synthesized) at the building base.

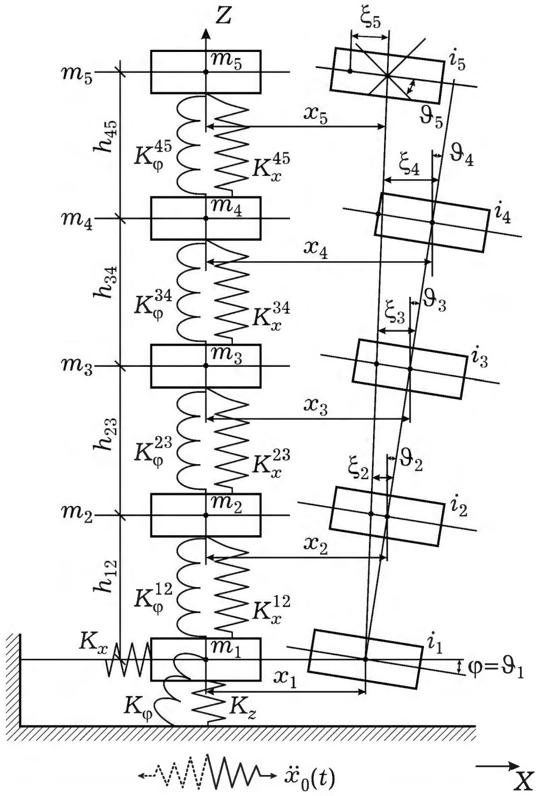

Fig. 2. The building flat CDM with taking into account the base and seismic isolation stiffness (K_x, K_z, K_φ), foundation mass m_1 and moment of inertia i_1, floor structures masses $m_2,\dots,m_5$ and moments of inertia $i_2,\dots,i_5$, and building structures shear $K_x^{12},\dots,K_x^{45}$ and angular $K_\varphi^{12},\dots,K_\varphi^{45}$ stiffnesses under seismic impact $x_0(t)$.

During the soil base horizontal vibrations $\mathbf{x}_0(t)$, the building foundation (mass m_1) displaces in the horizontal direction x_1 and rotates around the horizontal axis by angle φ (Fig. 2). The building storeys masses m_j gradually displace relative to the foundation (coordinates ξ_j) and rotate around the horizontal axis (coordinates ϑ_j), $j = 1, 2, \dots, 5$, see Fig. 2. Thus, the vectors of generalized coordinates without taking into account [9] and with taking into account the moments of inertia of the storeys masses are as follow:

$$\mathbf{q}^{\mathrm{T}} = (x_1, \xi_2, \xi_3, \xi_4, \xi_5, \varphi), \quad \mathbf{W}^{\mathrm{T}} = (x_1, \xi_2, \xi_3, \xi_4, \xi_5, \varphi, \vartheta_2, \vartheta_3, \vartheta_4, \vartheta_5).$$

To determine the absolute displacements and accelerations of the building foundation and storeys, the absolute coordinates should be used:

$$\mathbf{q}^{\mathrm{T}} = (x_1, x_2, x_3, x_4, x_5, \varphi, \vartheta_2, \vartheta_3, \vartheta_4, \vartheta_5).$$

The equation of the CDM motion is obtained using the Lagrange equations of the second kind [16, 20]:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right)+\frac{\partial}{\partial q_i}(U-T)=0\,,$$

where q_i are the generalized coordinates ($q_m = x_m$, $m = 1, 2, \ldots, 5$, $q_6 = \varphi$, $q_{n+5} = \vartheta_n$, $n = 2, \ldots, 5$), $\dot{q}_i$ are the generalized velocities, T is the kinetic energy of the system:

$$T=\frac{1}{2}\Big(m_1\dot{x}_1^2 + m_2\dot{x}_2^2 + m_3\dot{x}_3^2 + m_4\dot{x}_4^2 + m_5\dot{x}_5^2 +$$

$$+ i_{\text{total}}\dot{\varphi}^2 + i_2\dot{\vartheta}_2^2 + i_3\dot{\vartheta}_3^2 + i_4\dot{\vartheta}_4^2 + i_5\dot{\vartheta}_5^2 \Big),$$

and U is potential energy of the system:

$$U=\frac{1}{2}\Big(\Big(K_x x_1^2 + K_{12}(x_2 - x_1 - h_{12}\varphi)^2 + K_{23}(x_3 - x_2 - h_{23}\varphi)^2 +$$

$$+K_{34}(x_4 - x_3 - h_{34}\varphi)^2 \Big) + K_{45}(x_5 - x_4 - h_{45}\varphi)^2 +$$

$$+K_{\varphi}\varphi^2 + K_{\varphi}^{12}(\vartheta_2 - \varphi)^2 + K_{\varphi}^{23}(\vartheta_3 - \vartheta_2 - \varphi)^2 +$$

$$+K_{\varphi}^{34}(\vartheta_4 - \vartheta_3 - \varphi)^2 + K_{\varphi}^{45}(\vartheta_5 - \vartheta_4 - \varphi)^2 \Big).$$

Here, $i_{\text{total}} = I_{\text{IM}} + \sum_j m_j h_{j,\text{IM}}^2$, I_{IM} is the moment of inertia of the building relative to the horizontal axis passing through the center of gravity; $h_{j,\text{IM}}$ is the distance from the center of gravity to the jth mass of the building, and K_x, K_{12} K_{23}, K_{34}, K_{45}, K_{φ}, K_{φ}^{12}, K_{φ}^{23}, K_{φ}^{34}, K_{φ}^{45} are described in the legend of Fig. 2.

In the expanded form, the system (1) of differential equations (10 degrees of freedom) has the following form:

$$m_1\ddot{x}_1 + (K_x + K_{12})x_1 - K_{12}x_2 + H\,\mathrm{sgn}\,\dot{x}_1 + K_{12}h_{12}\varphi = -m_1\ddot{x}_0\,,$$

$$m_2\ddot{x}_2 - K_{12}x_1 + (K_{12} + K_{23})x_2 - K_{23}x_3 + (K_{23}h_{23} - K_{12}h_{12})\varphi = -m_2\ddot{x}_0\,,$$

$$m_3\ddot{x}_3 - K_{23}x_2 + (K_{23} + K_{34})x_3 - K_{34}x_4 + (K_{34}h_{34} - K_{23}h_{23})\varphi = -m_3\ddot{x}_0\,,$$

$$m_4\ddot{x}_4 - K_{34}x_3 + (K_{34} + K_{45})x_4 - K_{45}x_5 +$$

$$+(K_{45}h_{45} - K_{34}h_{34})\varphi = -m_4\ddot{x}_0\,,$$

$$m_5\ddot{x}_5 - K_{45}x_4 + K_{45}x_5 - K_{45}h_{45}\varphi = -m_5\ddot{x}_0\,,$$

$$i_{\text{total}}\ddot{\varphi} + K_{12}h_{12}x_1 + (K_{23}h_{23} - K_{12}h_{12})x_2 +$$

$$+(K_{34}h_{34} - K_{23}h_{23})x_3 + (K_{45}h_{45} - K_{34}h_{34})x_4 -$$

$$-K_{45}h_{45}x_5 + (K_{12}h_{12}^2 + K_{23}h_{23}^2 + K_{34}h_{34}^2 +$$

$$+K_{45}h_{45}^2 + K_{\varphi} + K_{\varphi}^{12})\varphi + (K_{\varphi}^{23} - K_{\varphi}^{12})\vartheta_2 +$$

$$+(K_{\varphi}^{34} - K_{\varphi}^{23})\vartheta_3 + (K_{\varphi}^{45} - K_{\varphi}^{34})\vartheta_4 - K_{\varphi}^{45}\vartheta_5 = 0\,,$$

$$i_2\ddot{\vartheta}_2 + (K_\varphi^{23} - K_\varphi^{12})\varphi + (K_\varphi^{12} + K_\varphi^{23})\vartheta_2 - K_\varphi^{23}\vartheta_3 = 0\,,$$

$$i_3\ddot{\vartheta}_3 + (K_\varphi^{34} - K_\varphi^{23})\varphi - K_\varphi^{23}\vartheta_2 + (K_\varphi^{23} + K_\varphi^{34})\vartheta_3 - K_\varphi^{34}\vartheta_4 = 0,$$

$$i_4\ddot{\vartheta}_4 + (K_\varphi^{45} - K_\varphi^{34})\varphi - K_\varphi^{34}\vartheta_4 + K_\varphi^{45}\vartheta_4 - K_\varphi^{45}\vartheta_5 = 0\,,$$

$$i_5\ddot{\vartheta}_5 - K_\varphi^{45}\varphi - K_\varphi^{45}\vartheta_4 + K_\varphi^{45}\vartheta_5 = 0\,. \qquad (2)$$

System (2) of the governing differential equations was solved numerically in Mathcad environment by the Runge – Kutta method.

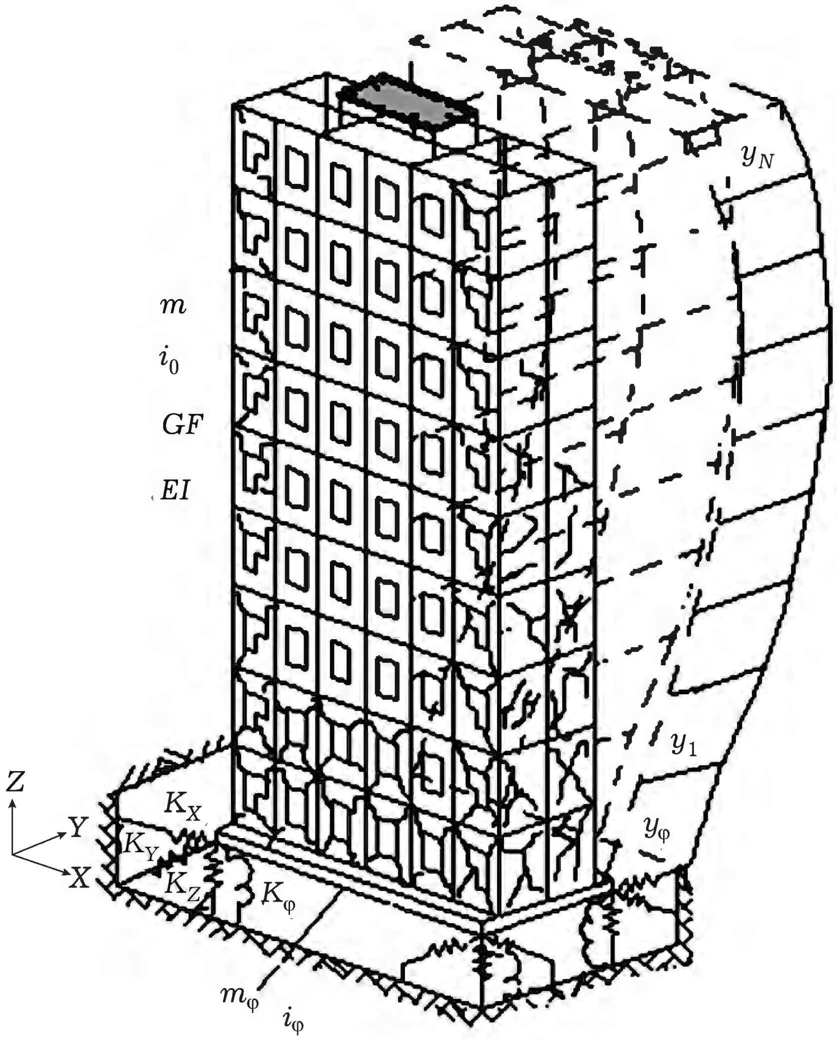

Fig. 3. The building spatial CDM taking into account the base and seismic isolation stiffnesses (K_x, K_y, K_z, K), foundation mass m_φ and moment of inertia i_φ, storeys structures masses m and moments of inertia i_0, storeys structures shear GF and bending EI stiffness.

2. The equation of motion for the spatial digital twin of a separate building under the railway transport dynamic effects. The numerical studies of the forced vibrations of the spatial multi-mass linear CDM of buildings (Fig. 3) under the railway transport effects are performed using the LIRA CAD software package (SP), in which the finite element method is implemented [19]. In the LIRA CAD SP, the building finite element spatial model is calculated for the railway transport dynamic effects (of low intensity, at which building structures work in an elastic phase) using the following system of differential equations with constant coefficients:

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}(\mathbf{x})\mathbf{x}(t) = -\mathbf{M}\ddot{\mathbf{x}}_0(t). \tag{3}$$

where $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are the constant matrices of the system masses, damping and stiffness; $\ddot{\mathbf{x}}(t), \dot{\mathbf{x}}(t)$, and $\mathbf{x}(t)$ are the accelerations, velocities and displacements vectors; $\ddot{\mathbf{x}}_0(t)$ is the kinematic load (soil acceleration at the building base) corresponding to time t.

The initial velocities are assumed to be zero, and the initial displacements are obtained from the equations system solution for the first loading $\mathbf{x}(t) = \mathbf{x}_1$.

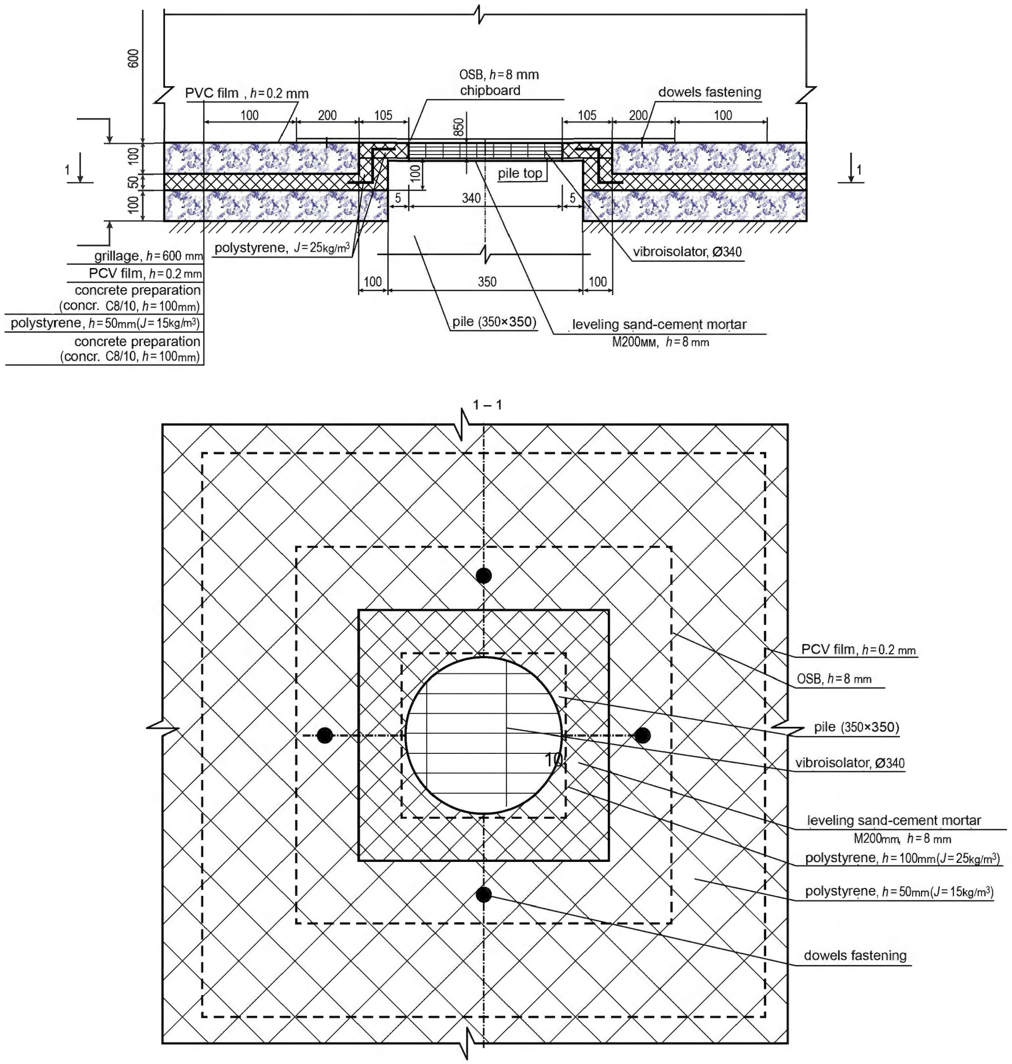

Fig. 4. Scheme of the building vibration and seismic protection system with rubber supports (vibration isolators with the diameter of 340mm and the height of 50mm) at the pile grid level: PVC film, OSB – oriented strand board, fasten with dowels, pile top, Styrofoam (kg / m^3), vibration isolator, grid, concrete bed (concrete of C8/10 grade, $h = 100\text{mm}$), pile, leveling sand grout.

If (3) is considered as a system of ordinary differential equations with constant coefficients, the velocities, accelerations, and displacements can be approximated by the finite difference expressions for displacements. Using the central differences method, the system of equations of motion for accelerations at time t can be written in the following form:

$$\left(\frac{2\mathbf{M}}{(\Delta t)^2}+\frac{\mathbf{C}}{\Delta t}+\mathbf{K}\right)\left(\mathbf{x}(t+\Delta t)+\mathbf{x}(t-\Delta t)\right)=2\left(-\mathbf{M}\ddot{\mathbf{x}}_0(t)+\right.$$
$$\left.+\frac{2\mathbf{M}}{(\Delta t)^2}\mathbf{x}(t)+\frac{\mathbf{C}}{\Delta t}\mathbf{x}(t-\Delta t)\right). \qquad (4)$$

The “new” displacements $\mathbf{x}(t+\Delta t)$ are determined taking into account the displacements $\mathbf{x}(t)$ and $\mathbf{x}(t-\Delta t)$ previously obtained when solving the system (4). Such integration schemes are called implicit integration schemes. The given integration scheme is called the modified method of central differences. Equations (4) are initial for solving both linear and nonlinear problems by direct dynamic calculations in the LIRA CAD software package [34].

During the numerical studies, the options are considered with an allowance for the dry friction forces during the vibrations of the reinforced concrete foundation on rubber supports relative to the base made of polystyrene foam (Fig. 4).

3. Experimental studies of the soil and buildings vibrations under the railway trains effects. The construction site is in a densely built-up area with neighboring highways and railways. Traffic near the construction site is unlimited during the day. The two-way traffic of passenger and freight trains at the Kyiv – Lviv railway section near the construction site is also without any restrictions.

In compliance with the design, the PDRC consists of three sections differing by the storeys number and dimensions in plan (Fig. 1). Section 1 is located at a minimum distance from the railway track (20–25 m). The railway track is ordinary one without any vibration isolation elements and with butt joints. Prior to the building construction start, the soil surface vibrations at the residential complex construction site were experimentally studied. A comparison of the experimental and allowable values of vibrations accelerations levels showed that under the railway trains effects the soil vibrations levels and predicted floors vibrations levels exceeded the values allowable for residential buildings by 6–12 dB (from two to four times). Thus, the necessity was proved to install a vibration protection system at the pile grid level so allowing to reduce the structures vibrations levels and ensure the comfortable living conditions in buildings.

The soil accelerations records obtained at the residential complex construction site are used in the dynamic analysis of the three sections spatial models for determining the predicted levels of building floors vibrations accelerations. The numbers of storeys in sections are as follows: 13, 6 and 10 in sections 3, 2 and 1, respectively. Each section is arranged on its own vibration-isolated pile foundation. The section 3 frame is made girderless of cast-in-place reinforced concrete with the stiffening cores in the zone of an elevator and stair blocks. In plan, the building floors have variable areas decreasing with height. The floor plan has the shape of a rectangular trapezoid. The section 2 frame is girderless of cast-in-place reinforced concrete with the stiffening cores in the elevator block zone. In plan, the section has a trapezoidal shape and adjoins sections 3 and 1. The section 1 frame is girderless of cast-in-place reinforced concrete with the stiffening cores in the elevator and stair blocks zone. The floor shape of section 1 is close to a parallelogram in plan.

According to [3], the construction site design seismicity is 7 points. Therefore, the construction should ensure the protection against both the ground railway transport dynamic effects and the earthquakes impacts.

The vibrometric studies of the soil, vibration-isolated grids and floor slabs were carried out over a period of two years during the construction of a residential complex with a system of vibration and seismic protection against railway trains effects and earthquakes.

In Fig. 5 the residential complex construction state at the time of the vibrometric studies in November 2018 is shown.

Fig. 5. The construction site view on November 22, 2018, after all storeys erection in the three sections of the residential complex.

Fig. 6. The buildings vibration and seismic protection system arrangement at the pile grid level (Fig. 2).

The final vibrometric studies and concrete grades determination by non-destructive control methods were conducted at the object in November 2018 after all storeys erection in three sections (6, 10, and 13 storeys). The vibrodynamic effects on the adjacent soil, grid (Fig. 6) and buildings floors were studied without moving railway trains (microseismic vibrations and natural seismicity of the Vrancea zone) and with them (man-made dynamic effects from railway trains and motor vehicle traffic). The dynamic studies were organized and conducted in compliance with the regulatory documents [2, 21]. During the experimental studies, the vibrometric equipment allowing to record the vibration signals in real time and carry out their processing with the octave and narrow-band spectra determination was used. The obtained vibration signals (vibrations accelerations) were recorded and processed by means of the Seismomonitoring software package [13].

Based on the performed studies, the vibrations accelerations instrumental records were obtained in real time during the vibrations of the adjacent soil and structures of residential complex sections 1, 2 and 3 in the 0.3 − 100 Hz frequency range under the railway trains dynamic effects.

As a result of the obtained records processing by the spectral analysis method, the levels of dynamic effects on the adjacent soil and structures of three building sections were determined, and the vibrations frequencies and maximum vibrations levels were recorded. In the 13- and 6-storey sections the recorded maximum levels of the floors vertical vibrations accelerations in the 16 Hz octave band reached 68 dB (Fig. 7), which was less than the 71 dB value allowable according to the Sanitary Standards [4].

Based on the comparison of the recorded levels of vibration effects on three sections structures in the residential complex and the values allowable according to regulatory documents, a conclusion was made as to ensuring the allowable values of vibrations levels under the moving trains dynamic effects.

4. Analysis for dynamic and seismic effects. The structural scheme of the residential 6, 10, and 13-storey buildings is a girdertless cast-in-place reinforced concrete frame (Fig. 1). The load-bearing vertical structures are composed of columns, pylons and stiffening cores. The typical storey height is 3.0 m. The storey floors and coverings are the 200 mm thick slabs of cast-in-place reinforced concrete, which connect the vertical elements and ensure the spatial building stiffness. The buildings foundations are cast-in-place reinforced concrete grids on a pile basis. The accepted piles cross-section is $350\text{mm} \times 350\text{mm}$.

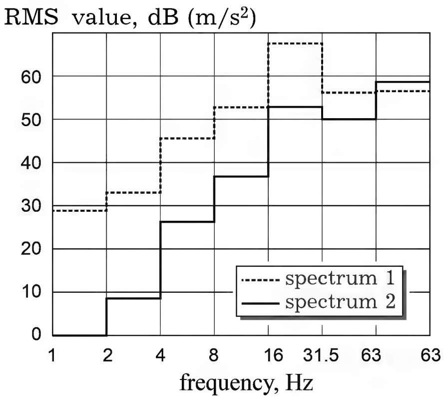

Fig. 7. The octave spectra of the vertical vibrations accelerations during the freight train passage (the vibration sensors 1 and 2 are installed on the 2nd storey floor in section 3 and on the 2nd storey floor in section 2, respectively): spectrum 1, spectrum 2, RMS value, dB (m/s^2), frequency (Hz).

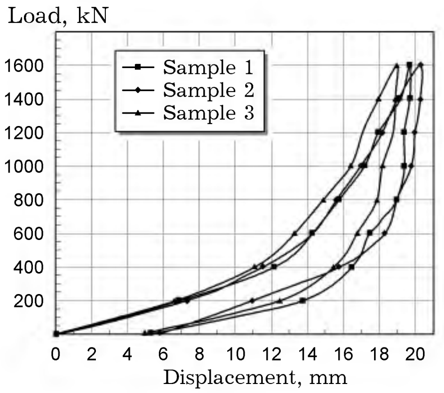

Fig. 8. The experimental nonlinear dependences of vertical displacements on loads (up to 1600kN) for the rubber isolators with 340mm of diameter and 50mm of height: samples *1*, *2*, and 3, load (kN), displacement (mm).

The pile grids are designed with 600 mm thickness in the 6-storey building and 800 mm thickness in the 10- and 13-storey buildings. For protecting against the railway trains dynamic effects, a vibration and seismic protection system is arranged (figures 4 and 6) based on the results of numerical studies and tests of rubber vibration isolators (Fig. 8). The rubber isolator with 340 mm diameter and 50 mm or 40 mm thickness (Fig. 6) is installed on each pile head before concreting the grid plate. The proposed solution of the vibration protection system was also tested in 10- and 27-storey residential buildings in Kyiv. The floors vibrations levels in twelve erected buildings did not exceed the values allowable under the railway trains dynamic effects (shallow and deep subway lines) according to the Sanitary Standards [6].

The spatial digital twins vibrations are calculated for the train dynamic effects in three sections of the residential complex with and without the vibration protection system (rubber vibration supports, on which the grid rests) using the LIRA CAD software package [23], in which the finite element method is implemented. The experimental nonlinear relationships of isolators vertical displacements and loads are shown in Fig. 8.

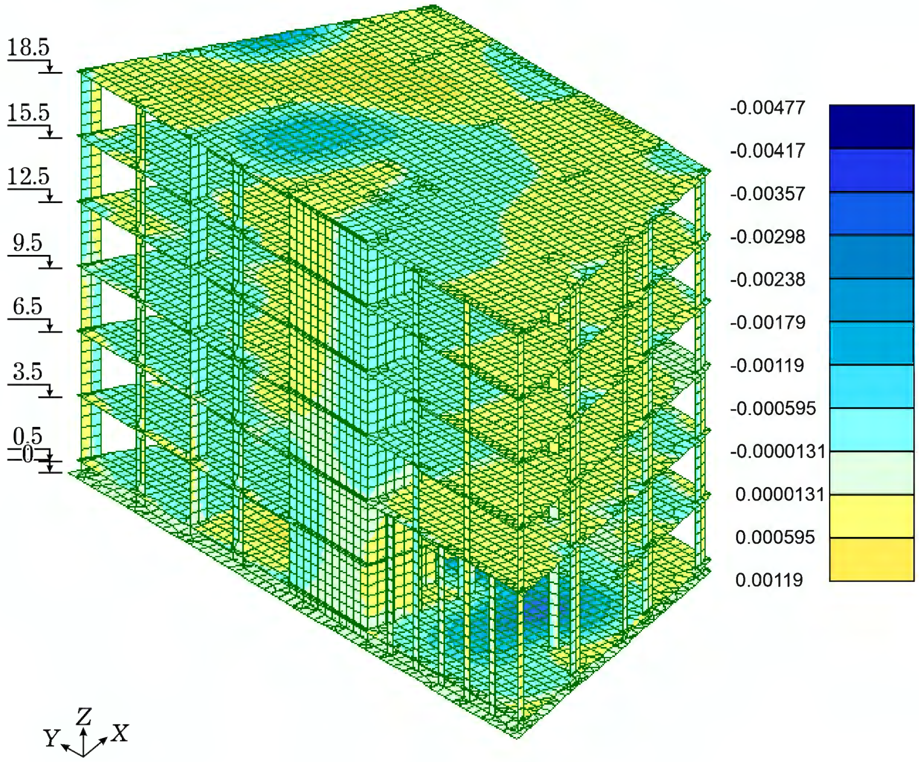

Fig. 9. The design vertical amplitudes of the 6-storey building floors displacements under the passenger train effects (the 55-th form of vibrations) in the absence of a vibration protection system: SEISMICS 2, component 55, isofields of displacements along Z(G), measurement units (mm), masses are collected from loadings 1 and 2.

The vertical vibrations frequencies in the 13- and 10-storey sections built on vibration supports (isolators with compressive stiffness $K_z = 105000\ \mathrm{kN/m}$) are 3.8 Hz and 4.1 Hz, respectively. The vertical vibrations frequency in the 6-storey building section on vibration supports (isolators with compressive stiffness $K_z = 67000\ \mathrm{kN/m}$) is 4.7 Hz.

For the floors vertical vibrations in the 6-storey building, the design levels of 0.00477 m are obtained in the vibration protection absence (Fig. 9), and of 0.000724 m with the vibration protection system installed (Fig. 10), i.e., the floors vibrations decrease by 6.6 times can be predicted. The same data are obtained when calculating the digital twins of the 10- and 13-storey sections.

The safety factor K_s for buildings overturning under seismic and wind loads is determined by the following expression: $K_s = M_m / M_s$, where M_m is the minimum resisting moment against a permanent load with respect to the edge row of vibration isolators, M_s is the maximum overturning moment for seismic or wind loads.

The calculations of overturning safety factors for the 13-storey building (the maximum height among three sections of the residential complex) confirm that for the 7 points intensity seismic effects the minimum design safety factor is 5.4. The minimum safety factor for wind effects is 101.6.

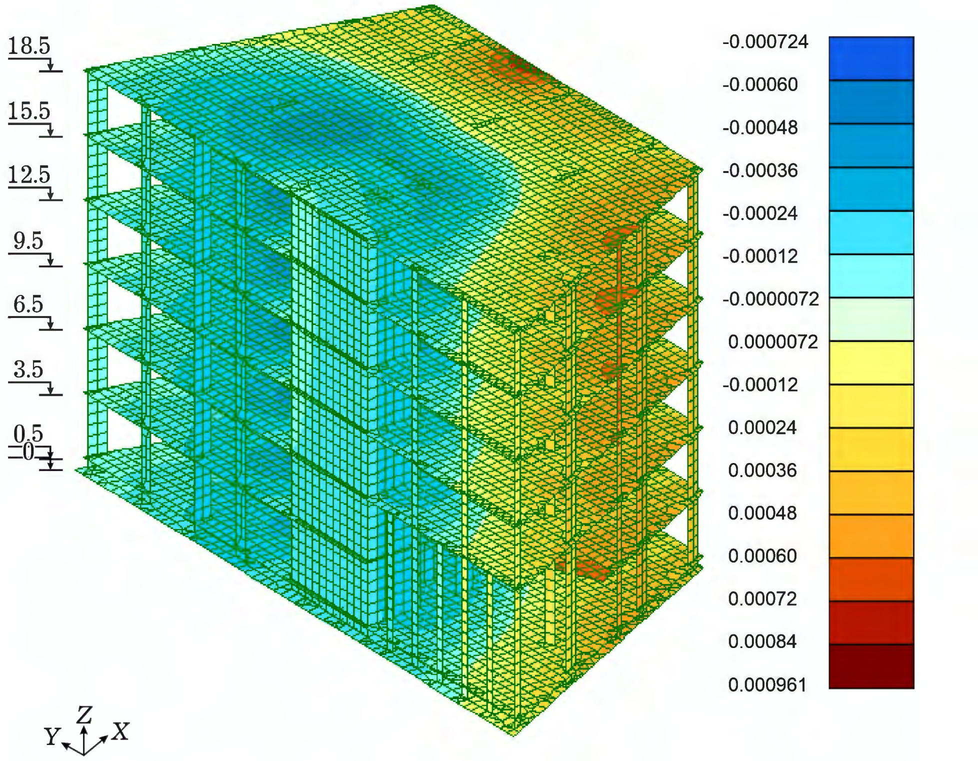

Fig. 10. The design vertical amplitudes of the floors displacements under the passenger train effects (the 10-th form of vibrations) in the 6-storey building with a vibration protection system: SEISMICS 2, component 10, isofields of displacements along $Z(G)$, measurement units (mm), masses are collected from loadings 1 and 2.

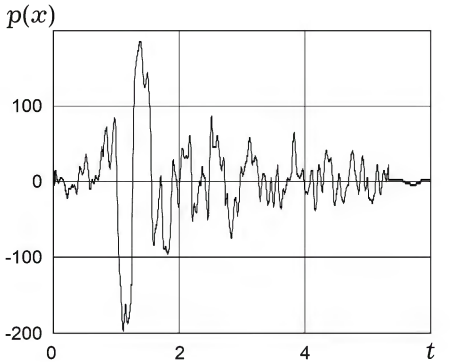

Fig. 11. Accelerogram of the long-period 1977 Bucharest earthquake of the 8 points intensity (the maximum ground acceleration $p = 2\ \mathrm{m/s^2}$ recorded at the earthquake beginning, time $t = 1.0\,\mathrm{sec}$) [24].

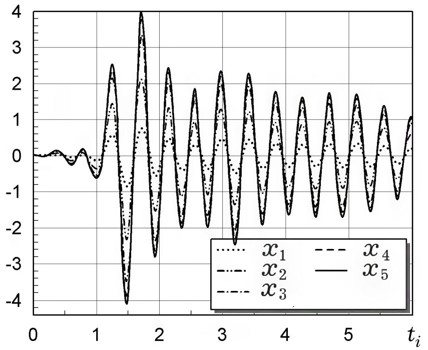

Fig. 12. The horizontal displacements ($\mathrm{m} \times 10^{-2}$) of the building foundation (x_1) and storeys ($x_2, \ldots, x_5$) in time t (s) under the impact of the 1977 Bucharest earthquake of 8 points intensity (the frictional force is assumed as 0.8% of the building weight).

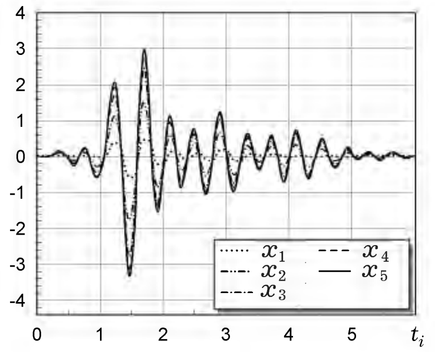

Fig. 13. The horizontal displacements ($\mathrm{m} \times 10^{-2}$) of the building foundation (x_1) and storeys ($x_2, \ldots, x_5$) in time t (s) under the impact of the 1977 Bucharest earthquake of 8 points intensity (the frictional force is assumed as 8% of the building weight).

5. The results of the building non-linear flat model analysis for seismic effects. Earthquakes in the Vrancea area (Romania) are the most dangerous for the city of Lviv [3]. Therefore, the nonlinear flat model (Fig. 2) is analyzed for the effects of the accelerogram (Fig. 11) recorded during the devastating 1977 Bucharest earthquake. The numerical studies of the nonlinear equations (1) are carried out in the Mathcad environment. The building foundation mass of 1200 tons and the storeys mass of 500 tons are assumed.The analysis results show (figures 12 and 13) that it is possible to additionally reduce the building foundation displacements during earthquakes by 1.5 times if the frictional forces are taken into account.

Conclusion. The theoretical and experimental dynamic surveys of the buildings complex at 26 Pid Dubom St. in the city of Lviv based on the digital twins technology included the experimental studies of the construction site soil surface and buildings grids and floors structures using the IoT; the numerical studies of the spatial digital twins of 6-, 10- and 13-storey buildings with and without a vibration protection system for the dynamic effects of railway trains; the numerical studies of the flat digital twins of 6, 10 and 13-storey buildings for the Vrancea zone seismic effects.

Based on the results of the theoretical and experimental dynamic studies, the following conclusions can be drawn.

1. The comparison of the experimental and allowable values of the vibration accelerations levels shows that under the railway trains effects the soil vibration levels exceed the values allowable for residential buildings by $6-12\,\mathrm{dB}$ (from two to four times). That proves the necessity of the vibration protection system arrangement at the pile grid level for lowering the structures vibration levels and ensuring the comfortable living conditions in buildings.

2. The numerical studies of the spatial digital twins of three residential complex sections are performed under the railway trains effects with and without a vibration protection system.

3. To ensure the comfortable living conditions in the residential complex buildings, the vibration and seismic protection system at the pile foundation level is developed and applied. The design frequency of the natural vertical vibrations of buildings with the vibration supports is $3.8-4.7\,\mathrm{Hz}$, which is by 3.12 times less than the soil forced vibrations frequencies ($15-80$ Hz) due to the railway trains effects. The design and experimental data analysis shows that, if the vibration isolation is installed, the floors vibrations levels do not exceed the levels permitted by the Sanitary Standards for residential

buildings. In the vibration protection absence, the design levels of floors vertical vibrations exceed the allowable values by 1.5 – 4 times (from 2.9 dB to 13.0 dB).

4. The proposed system of the building vibration and seismic protection arranged at the pile foundation level ensures both the damping in the rubber supports (up to 5% of the critical damping) and the friction forces, which allows to additionally reduce the building foundation displacements during earthquakes by 1.5 times.

5. The minimum design factor of safety against buildings overturning is 5.4 in the case of seismic loads (determined at 7 points) and 6.5 under the wind effects.

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ГІБРИДНИЙ ЧИСЛОВИЙ МЕТОД РОЗРАХУНКУ СЕЙСМОЗАХИСТУ БУДІВЕЛЬ НА ОСНОВІ ЦИФРОВИХ ДВІЙНИКІВ

Наведено результати числових та експериментальних досліджень вібро-сейсмозахисту житлових будинків з використанням гумових ізоляторів українського виробництва з натуральної гуми. Числові дослідження вертикальних коливань будівлі з гумовими опорами на рівні залізобетонної сітки виконано з використанням динамічних цифрових двійників, розроблених на основі методу скінченних елементів. Числові дослідження коливань цифрових двійників виконано з використанням записів віброприскорень ґрунту, отриманих внаслідок проходження залізничних поїздів, а також ефектів, визначених акселерограмами землетрусів. Виконано розрахунки будівель на сейсмічних опорах з урахуванням сейсмічних навантажень з визначенням коефіцієнтів безпеки щодо падіння житлового будинку. Показано, що вирішення проблеми вібро- та сейсмозахисту будівель є можливим при використанні в якості ізоляторів гумових елементів, які мають нелінійну залежність жорсткості від навантаження.

Ключові слова: *гібридний чисельний метод, цифрові двійники, динамічні та неруйнівні дослідження, гумові ізолятори, віброізоляційна сітка, зона землетрусу Вранча.*

[1] Institute of Telecommunications and Global Information Space, NAS of Ukraine, Kyiv,
[2] National University of Life and Environmental Sciences of Ukraine, Kyiv,
[3] State Enterprise “The State Research Institute of Building Constructions”, Kyiv,
[4] National Technical University of Ukraine “Igor Sikorsky Kyiv Polytechnic Institute”, Kyiv

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