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STUDY OF THE INFLUENCE OF METRO LOADS ON THE DESTRUCTION OF NEARBY BUILDINGS AND CONSTRUCTION STRUCTURES USING BIM TECHNOLOGIES

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Abstract. The authors studied the influence of metro loads on the destruction of nearby buildings and construction structures with the help of BIM technologies in order to eliminate the human factor at the design stage. In the study, numerical modeling was carried out using the LIRA-SAPR software package, and dynamic loadings were set by the time integration technique. The suggested technique involved a nonlinear dynamic analysis conducted considering the time factor; the parameters of the stress-strain state (displacement, force, stress) were determined at each moment of exposure, changing the rigid characteristics of the building structures. The authors conducted a structural assessment of an unfinished construction facility, considering the vibrodynamic loads of the metro. Numerous models were adopted as the structural designs of buildings that consider various impact factors, such as nonlinear soil behavior and permanent action and the nature of dynamic loads. The comparison with experimental data confirmed the theoretical and computational parts of the developed technique. The study determined the vibrodynamic impact of the metro on the construction structures. Verification of the developed methodology based on BIM technologies was carried out by comparing the results of numerical experiments with the results of subsequent full-scale vibration tests.

Keywords: metro, BIM technologies, finite element method, vibrodynamic loads.

Introduction

In Ukraine, as well as in other highly developed countries of the world, there is a constant expansion of large cities, which require a constant increase in construction sites, as well as direct access to them and, accordingly, ways to solve logistics problems. Since the main buildings and constructions in the ever-growing urbanization are civil and public buildings, the most demanded logistical solution is the construction of a metro, or the continuation of the existing one branches. Therefore, at present, the quality of large settlements life directly depends on the development of not just logistical routes, but the metro, since there are no practical and economic analogues of the logistical movement of passenger traffic yet.

In turn, the metro, like any other rail transport, especially located in tunnels, produces a lot of noise and is also a source of vibration. As a rule, the construction of new metro lines takes place in the existing urban constructions with well-established buildings and structures, while there is a violation of the density and condition of the soil, as well as an increase in vibration and noise in constructions nearby or located above the metro lines, and new buildings are being elevated near already existing stations and metro tunnels.

The protection of buildings and constructions from vibrodynamic loads, which began to arise not only at the time of laying the metro lines, but also during its operation and directly during the course of the subway rolling stock, has become topical at the present stage of building, since at the present time the construction of shallow tunnels prevails. Comparing with the arrangement of deep tunnels, this method has technical and economic advantages and is the main one today. The current regulations on the metro design or buildings and constructions do not actually regulate the issue of assessing the permissible

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vibration levels (in amplitude and frequency) of the building itself as a whole, its individual structural elements, the ground base in the area of the building and the metro line (Borisov et al., 2007; Ministry of Regional Development of Ukraine, 2011, 2019).

There are references to sanitary standards, where the permissible levels of noise and vibration loads in civil and public buildings are indicated (Verkhovna Rada of Ukraine, 1999a, 1999b). It is generally accepted that if the levels of vibration and noise are within the limit values, then the bearing structures capacity is satisfactory. However, these assumptions are false and have no scientific basis, since such measurements are carried out at the floor level of the premises and on the ground surface, which is not enough to determine the stress-strain state of structures. In the traditional dynamics of buildings and constructions, the approach of building structures of natural frequencies oscillations prevails, the imposition of these oscillations with the load frequency leads to the manifestation of resonance (Ministry of Regional Development of Ukraine, 2014). However, both in Ukraine and abroad, designers are increasingly faced with significant damage to structurally complex, spatially located buildings and infrastructure facilities. The scholars conducted independent research and found that the reasons behind the above were not manifestations of resonance in the initial design. Furthermore, no technological violations were identified as a result of construction work (Kulyabko, 2010; Banakh, 2012).

A standard construction is designed and calculated using elementary approaches that take into account the strength of materials, theoretical and structural mechanics, but a situation may arise in which the system will be on the verge of critical stability (Bazhenov et al., 2005). Vibrodynamic fluctuations also have a negative impact on the soil itself. Compaction occurs, and sometimes unaccounted for shrinkage and the formation of landslides. Accordingly, destruction can occur not only in soils located directly under the line of the operated metro line, but also in soils located in these loads influence zone, causing additional vibrations of buildings and constructions, as well as changing the bearing capacity of soils (their physical and mechanical properties).

Accordingly, the adoption of measures to eliminate existing loads is not a full-fledged method for resolving the issue, and the development of objective solutions at the design stage is relevant, which will take into account comprehensive information not only about the impact of the metro life on existing buildings and constructions, but also consideration of the very survivability of structures during vibrodynamic loads.

BIM technologies are undoubtedly used to ensure safety, viability, direct energy saving, and reduction of material consumption in the design of buildings, constructions, and individual structures that fit into a given complex. However, the main requirement for direct implementation of BIM technologies is to design such a level that will consider the city network, its improvement, and the processes of the life cycle of existing and planned construction objects that must be operated during the life cycle allotted by the standards (Duan & Liu, 2023).

Many numerical experiments are needed to calculate the extent of the impact of deep and shallow metro laying on buildings. Numerical experiments make it possible to vary the input parameters repeatedly in a wide range of operating conditions of such a complex system as "the above-ground part of a building – soil – soil – metro tunnel with a moving train". This implementation saves time when solving several similar problems and allows drawing appropriate conclusions about the stress-strain state of load-bearing structures located in the area of constant impact of vibrodynamic loads. Numerical simulation is most expediently performed with the help of LIRA-SAPR, a comprehensive software package that benefits from BIM technology. Dynamic effects are set by the time integration method.

Researchers predominantly pay attention to railway transport and its elements, such as the dynamics of the rolling stock, railway tracks, bridges, etc. The modeling of ground waves is considered in some scientific works. The state of structures located nearby railways or the metro attracts incomparably less attention among scholars. An analytical review of the works devoted to the study of transport vibration shows that their main drawback is the solution to specific individual problems. In the field of railway facilities, these problems concern the reliable operation of rolling stock and the preservation of main transport routes (Marienkov, 2013). In rare cases, the problems involve ensuring the safety of industrial buildings and structures directly adjacent to railway tracks. In the context of urban public utilities, scholars predominantly consider such problems as the preservation of road bridges and the prevention of unacceptably high vibrations from a metro of shallow laying (Bashinsky, 2018).

In the scientific works, attention is mainly paid to vibration loads and their negative impact on the soil. It is shown that vibration under dynamic loads reduces shear resistance and friction forces between soil particles, while strong impulse actions can cause additional rock slippage and subsidence (Barabash et al., 2016b). At a particular vibration frequency, the friction force between particles in loose soils can decrease so much that soil acquires the properties of a viscous liquid, even with a small amount of water in it. For example, the shear resistance and the angle of internal friction decrease under vibrodynamic loads. Thus, permanent vibrodynamic metro loads affect the physical and mechanical properties of soils and the bearing capacity of operated, erected, or reconstructed structures of buildings.

It is impossible to give a complete and reliable assessment of these impacts using only instrumental methods. Many problems of propagation of dynamic waves do not have simple solutions. They are mainly studied on numerical models that do not fully reflect the operation of soil grounds and building structures. Therefore, it is essential to develop complex numerical methods that provide objective and comprehensive information about the actual stress-strain state of buildings and structures under vibrodynamic loads of this type (Banakh, 2011c). The analysis of the literature sources allowed the authors of this article to preliminarily consider measures to counter vibrodynamic loads in order to prevent damage and further destruction of structures. These measures can be as follows: to strengthen or install a vibration damper at the level of foundations, to install a damper directly in the metro tunnel, or to equip protective screens in the ground between the building structures and the metro tunnel.

There are practically no studies that consider the dynamics of the "vehicle – soil – structure" systems. The fundamentals of statics and dynamics of building and construction structures were developed in classical works by Newmark and Rosenblueth (1971), Weaver Jr. et al. (1991), and others. The issues of the dynamics of building structures, soil foundations, and the modeling of their joint work were the subjects of research by such scientists as Niemchynov and Kaliukh (2004), Dorofeev (2006), Kulyabko (2010), and Marienkov (2013). Studies by Ukrainian scientists suggest that seismic hazard in Ukraine is significantly underestimated. About 20% of the population of Ukraine lives in seismically hazardous regions. However, earthquakes systematically find errors in design and construction (even the smallest errors); this feature of earthquake-resistant construction highlights the challenges in solving this problem (Niemchynov & Kaliukh, 2004). At the same time, active urban construction exacerbates the danger of other dynamic impacts. Numerous underground workings can lead to a sharp rise in groundwater and thus increase the risk of a negative dynamic impact of movable vehicles (Kulyabko, 2010).

Various design measures for vibration protection are being developed, along with experimental and theoretical assessments of vibrations of soil and structures caused by the movement of underground trains and ground railway transport. These measures include equipping foundations with pre-compressed rubber plates, constructing pile foundations with protective screens, placing additional massive blocks near the railway track, placing buildings on a concrete pad, etc. During the construction of railway or metro structures, much attention is paid to the influence of the technical condition of the railway track and rolling stock on the vibrodynamic loads generated by them. The heaviest loads on railway tracks occur during the passage of rolling stock with defective wheels. Experimental studies of shock loads generated by the wheel passing through steel plates installed on both rail tracks, with a thickness equal to the wheel defect, show that the impacts of wheels with potholes create dynamic loads that exceed static ones by 5–10 times (Hughes, 2016). Scientists conducted experimental studies to determine the amplitudes of vibrations of soil embankments generated by rolling stock with increased axial and linear loads. There also were studies conducted to identify influence zones of dynamic train loads in the subgrade and assess the levels of vertical dynamic loads on the upper structure of the railway track from wagons with a carrying capacity of 70 to 125 tons, which moved at different speeds (Kun & Onargan, 2013; Komandyrov, 2020).

Scientific publications in foreign scientific and technical literature are, as a rule, of a theoretical nature. The percentage of experimental studies is quite low and is rapidly decreasing. Therefore, it is relevant to develop numerical methods to simulate the influence of the rolling stock of metro or railway transport on the nearby building or construction structures. Notably, structural vibration is directly related to the loss of bearing capacity, which, in turn, is acutely manifested in metal structures. Furthermore, the problem of transport vibration influence on the stability of soils at the base of buildings and structures remains unresolved. For example, a significant part of the unstable rocks has relatively low structural properties and thus is sensitive to external influences. The unsatisfactory stability of such foundations is manifested in additional and differential settlement caused by water-table waves that are not considered in the design, negative impacts on soils, and vibrations from urban transport. Thus, the calculation methodology of this study was based on the above scientific works.

The authors studied the problem of assessing the technical condition of construction facilities located in the zone of influence of vibrodynamic loads of transport highways. The reasons for the deterioration in the technical condition of the load-bearing structures of buildings and constructures operated near high-speed rail lines were considered. The authors presented an intellectual model for assessing the technical condition of construction facilities. At the same time, the authors strove to substantiate models and methods for assessing the technical condition of construction facilities located in the zone of influence of vibrodynamic loads. In order to provide information and analytical support for construction and technical expertise, it was proposed to use BIM technology and the Takagi-Sugeno-Kang fuzzy neural network. The use of this model makes it possible to automate the assessment of the technical condition of facilities qualified for construction and technical expertise. The authors substantiated the expediency of training an artificial fuzzy neural network based on the results of the analysis of numerous observations and experiments using the LIRA SAPR software package. The practical application of the results of the study is expected in the implementation of a support system for construction and technical expertise on the justification of proposals on the location and conditions for the construction of a new facility in dense urban areas near highways. Furthermore, the study showed frequency vibrations and their range from 20 to 80 Hz.

The *aim* of this work is to determine the influence of the metro (vidrodynamic loads) on the building and construction structures located in the operated area, as well as to determine the stress-strain state of structures using computer modeling, which includes BIM technologies. For this, the following *tasks* were proposed:

1. To provide a theoretical study of the stress-strain state of building and construction structures under the existing vibrodynamic effects of the metro.
2. To assess the influence of the metro depth on the supporting structures of buildings and constructions, as well as the dynamic propagation intensity degree.
3. To develop a structure that takes into account the influence of vibrodynamic stresses during the life cycle of structures (time) using a mathematical model.
4. To improve the calculation models of structures, taking into account their nonlinear operation, using LIRA-SAPR.

Since cost planning and construction safety have always been a priority in urban planning, the solution to the set goals and objectives is relevant.

1. Materials and methods

In the modern world, master plans for metropolis infrastructure development are constantly improving; they consider not only existing transport interchanges and related communications but immediate prospects for the development of logistics chains, including transport networks, approved territories for new construction, a set of measures and approaches for renovation, repair work and reconstruction of old residential and industrial stock. As a result, it becomes possible to make a forecast of man-made factors – vibration sources that are already present or are just being designed, or will soon appear near existing buildings. Vibration waves that travel in the soil have a spatial nature and affect the bases and foundations initially and, subsequently, adjoining structures that make up the structure matrix due to their proximity to the metro and other logistical components that cause vibration and dynamic loads (Kril, 2008; Guo et al., 2022).

Initially, an action of a vibrational nature is manifested, in the future, this effect, as a rule, is supplemented by sound waves (noises). The influence of vibrations is not without trace. People who are inside buildings and constructions often perceive this kind of influence painfully, especially when the frequencies coincide with the frequencies of the human body organs vital activity. Also, sound influence (noise), which is expressed in the form of low-frequency noise, can cause headaches, nausea, vomiting, and cardiovascular problems in a person. Such adverse effects negatively affect not only the well-being of a person, but also the impact on the performance and working climate in the building itself.

Vibration influences also affect the viability of the buildings themselves and cause fatigue of the structures. Over time, fatigue can accumulate in structures in the form of unaccounted for stresses, cracking and delamination of concrete occur, accelerated wear of materials, which leads to the need for unplanned repairs and other operating costs that cause economic damage and the likelihood of a force majeure situation.

As for the metro, as the main city infrastructure logistical artery, in view of the fact that its component produces an increased emission of noise and vibration waves, since the rail connections resonate when exposed to rolling stock. At the same time, the metro itself, as well as the construction of its new branches, is in direct contact with the existing urban structure and the habitats of people and animals. As well as the construction of new residential areas and other critical infrastructure often takes place near the location of metro stations.

In Ukraine, there are no current regulatory documents that determine the permissible levels of vibration from traffic specifically for the buildings and construction structures. The main documents in this area are GOST 12.1.012-2004 (Interstate Council for Standardization, Metrology and Certification, 2004), CH 2.2.4 / 2.1.8.566-96 (Ministry of Regional Development of Ukraine, 1996), DSN 3.3.6.042-99 (Verkhovna Rada of Ukraine, 1999b). Vibration impact on people being or living in such buildings is established under the above norms. This information is not enough to consider and prevent transport vibration impacts.

Simultaneously, there are a number of international documents that establish frequency-dependent criteria for vibration assessment. Below are the standards that are directly used in international documentation to determine the criteria for the vibration impact on buildings and constructions.

The State Standard of Germany (German Institute for Standardization, 1999) describes the maximum values for peak velocities at the foundation of a building, for short-term and long-term vibration. Buildings and structures are divided into the following categories:

1. Business buildings; industrial buildings and constructions having a similar design;
2. Residential houses and buildings having a similar design or purpose;
3. Buildings that do not belong to the first or second category, as well as having a high social significance (monuments of architectural heritage of various categories).

The influence on the destructive ability of a building and constructions, in particular, depends on the vibration effect, which determines not only the category of the building, the intensity and the spectrum itself and the amplitude of the vibrations that are transmitted through the contacting matter (soil in particular), but also depends on the characteristics of the material and its ability to transmit dynamic loads, as well as from load-bearing and enclosing structures and directly from the connection matrix itself and the structure model. A number of parameters also have a significant influence, such as the distance from the metro to the constructions or structure, the ability of the material to dampen vibrations, or vice versa, to carry them out at the stages of new development, it must be taken into account that the design frequency of the vibration load of tubing is 28–35 Hz, (prefabricated part) and up to 60–70 Hz (monolithic part). And the transmission is directly carried out through the ground or foundation directly to the existing or under construction structure. The timing of the transmitted vibration load is equal to the time-speed ratio of the moving subway train and is equal to 8–15 seconds (Banakh, 2011a, 2012).

As noted earlier, dynamic vibration is caused by periodic contact (impact) of the train wheel when passing through a rail junction. The dynamic impact arising from this impact is extinguished until the rest of the wheels pass through the rail joint. In this case, an additional vibration occurs, periodically falling into the rhythm of the existing one directly from the curvature of the rails and the rough surface of the rail bed, as well as from the effect of the "wobble" of the train during movement. Taking into account such an impact, vibration in the periodicals of 25...50 Hz is predominant (Barabash et al., 2016a). At the same time, such an impact can be equal to the frequency of tunnel tubing, then even taking into account the vibration damping capabilities of the soil and the structure of the track itself, regardless of whether there is vibration isolation or not, the vibrodynamic influence can increase.

Therefore, it is impossible to always talk about one predominant frequency of the metro impact on the supporting structures of the building. In this regard, without considering the damping capacity of the tunnel tubing and the upper structure of the metro, it is necessary to expand the frequency range from 20 to 70 Hz (Banakh, 2011b, 2011c). However, Komandyrov (2020) noted in his work that this range should be expanded from 20 to 80 Hz. Simultaneously, it is also necessary to take into account the fact that natural frequencies of buildings, as a rule, can fall into this range, which is especially dangerous. Accordingly, it is necessary to investigate the influence of soil dynamics and enclosing structures from various dynamic loads on the structure. Consider this question mathematically.

In the case of calculating the structural elements of the building from the loads impact of the metro rolling stock, it is very important to take into account the nature of the structure movement and the change in the non-linear deformable state of the building in a certain period of time. For the correct design of a building using a mathematical model, it is necessary to take into account additional parameters (in order to increase the accuracy of calculations), in addition to the geometry itself, also consider the physical and mechanical properties of materials of building structures and soils; initial stresses and deformations in the soil during the construction of the structure, as well as its initial stresses; external dynamic actions, directly their character (Kiselev & Berzhinsky, 2008).

The calculated dynamic load from the movement of the metro is given by the equations of sinusoidal effects:

$$A \times \sin(\omega \times t + \varphi), \qquad (1)$$

where A – amplitude; ω – frequency; φ – phase shift (which shows the beginning and end of the load impact).

The authors also set the following: amplitude of the force of impact (P); impact frequency in radians; phase offset in degrees, and start and end times in seconds.

To solve the problems of dynamic analysis of building structures, the following methods are used: decomposition according to its own forms; unification of the motion equations in time by a direct method. Expansion in its forms (in the methodological sense) should be applied only within the framework of a linear calculation, since the nonlinear theory of calculation does not accept the principle of superposition and this calculation will be incorrect. Using this method, it is possible to solve the following problems of dynamic impact: the action of an impulse; impact action; wind impact; forced harmonic vibrations; spectral seismic; storey (nodal) response spectra.

When solving problems of the metro influence calculating, it is advisable to use the methods of direct integration, due to the fact that they have a more generalized structure and can be used for dynamic calculation of structures (formation of mathematical problems) taking into account time factors. For objects of increased danger (responsibility class CC3) and for housing stock buildings (including public ones) with a height of 73.5 m to 100 m (responsibility class CC2), it is important to know what technical condition the supporting structures and construction elements of the building will be in when given dynamic or seismic action.

According to the current DBN V. 1.2-14:2018 (Ministry of Regional Development of Ukraine, 2018), the consequence class of a building or construction site is determined by the level of possible material losses and (or) social losses caused by the operation termination or the loss of the facility integrity. The possible social costs of failure of a building or structure should be assessed depending on the following risk factors:

1. Threat to human health and life;
2. Sharp environmental deterioration in the area adjacent to the facility (for example, in the event of the destruction of storage facilities for toxic liquids or gases, failure of sewage treatment facilities, etc.);
3. Loss of historical and cultural monuments or other spiritual values of society;
4. Failure of communication systems and networks, energy supply, transport, or other elements of critical or security services;
5. Impossibility to organize the provision of first aid to victims of accidents and natural disasters;
6. Threat to a country's defense capacity.

Therefore, one should verify the degree of construction project complexity taking into account consequence classes. There are three consequence classes (CC1, CC2, and CC3), and their classification is guided by the following scheme:

- CC1 corresponds to the first and second categories of complexity;
- CC2 corresponds to the third and fourth categories of complexity;
- CC3 corresponds to the fifth category of complexity.

Table 1. The criteria for consequence classes defined according to Resolution No. 778

Consequence class of construction site	Features of possible consequences of failure of a building or structure					
	Possible threat to human health and life, people			extent of possible economic damage, people	loss of cultural monuments; category of facility	failure of communication systems and networks, energy supply, transport, other engineering networks; level
	who are constantly at the facility	who are periodically facility	who are outside the facility			
CC3 (high consequence)	over 400	over 1000	over 50000	over 150000	of national importance	nation-wide
CC2 (medium consequence)	from 50 up to 400	from 50 up to 1000	from 100 up to 50000	from 2000 up to 150000	of local importance	regional, local
CC3 (low consequence)	up to 50	up to 50	up to 100	up to 2000	–	–

The Cabinet of Ministers of Ukraine is entrusted with assigning facilities to the fourth and fifth categories of complexity. The procedure for assigning construction facilities to the fourth and fifth categories of complexity was approved by Resolution No. 778 of the Cabinet of Ministers (Table 1).

Since the structures of buildings can be quite complex, and the installed equipment amount is quite significant, it is rather difficult to perform modeling of the design scheme of the building. Therefore, the best way out of this situation is to use the method of subsystems.

2. Results

2.1. Technique for modeling the impact of the metro on the supporting structures at the stage of a high-rise building installation

To study the behavior of the load-bearing structures of buildings and constructions located near the metro tunnels, the author developed computer models (Perelmuter & Slivker, 2002), with different types of load-bearing structures and soil, in which the vibrodynamic impact of the subway is simulated, as shallow, and deep type of laying.

Numerical simulation was carried out using the LIRA-SAPR software package, dynamic effects are set by the time integration method. The numerical experiments presented in this paper make it possible to provide not just mathematical programming of individual components that show the existing loads, but directly simulate the interconnected system "aerial part of the building – base – soil – subway tubing with rolling stock". At the same time, empirical studies are replaced by mathematical calculation. The creation of such a numerical model makes it possible to accurately take into account the nonlinear deformations of load-bearing structures, while saving time and money for the empirical part of the calculations. It also allows you to optimize the consumption of materials for structures that are in the zone of constant vibrodynamic loads exposure (Gorodetskiy et al., 2015).

The computer model was created using the LIRA-SAPR software package and the DYNAMICS+ subsystem (Barabash, 2014; Barabash et al., 2016b, 2017a, 2017b). The vertical dynamic load along the Z axis is set with an oscillation amplitude $\omega = 35$ rad, which is equal to $f = 50$ Hz, the number of oscillation modes is 100.

The calculation was performed with an integration step of 0.1 s, the integration time was 30 s. Figures 1 and 2 show the design schemes, which reflect the form taken by the design scheme of the building at $t = 16$ s, vibration acceleration at the control point in Figure 3.

During control measurements of dynamic loads in residential buildings from subway tubing, which is a detonating surface, as a parameter taken as a norm, we take the vibration acceleration parameter, when setting the extremum, they rely on the threshold of a living organism limiting perception, which in turn allows us to estimate the limits of vibration exposure in extrema (maximum and minimum values of the parameter we have chosen) (Figure 3).

Table 2 gives a comparative analysis of the permissible RMS values of vibration accelerations according to ISO Code 4866 (International Organization for Standardization, 2010), and comparison with the experimental results (obtained in a numerical experiment).

After analyzing the numerical experiment, we can conclude that regular metro vibrations, especially when rolling stock is braking (with a frequency of about 50 Hz), cause such a dynamic vibration force that can lead to the transmission of vibrations not only to the soil and foundations of a nearby building, but also directly to every adjacent structure, which can lead to the formation and further propagation and opening of cracks and further destruction of load-bearing structures. Exceeding the permissible mean square values of vibration accelerations in some cases can be more than 2 times.

2.2. Finite elements calculation method

For the study, a building of a retail and office complex with a height of more than 60 meters was chosen. For comparison, changes in the internal forces of the building supporting structures under dynamic loads were selected. When solving the problem, the structures were made in two versions: a metal frame in the first version and reinforced concrete in the second (the same calculation method is applicable to a building with reinforced concrete columns) (Figure 4).

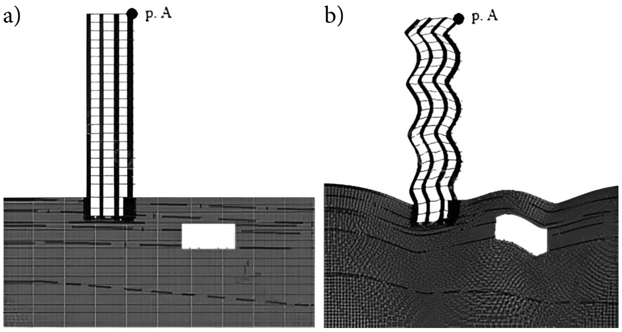


Figure 1. The considered scheme for taking into account the influence of shallow laying tubing: a – to dynamic impact; b – after dynamic influence

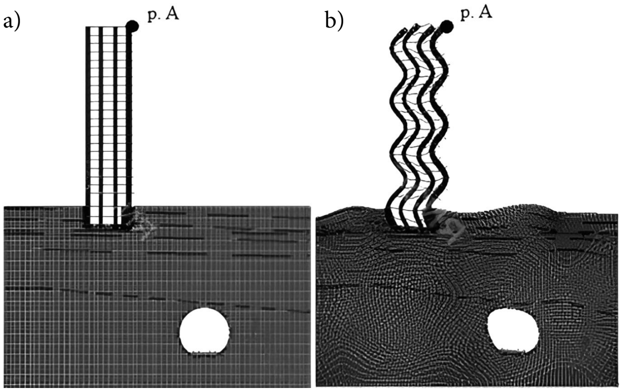


Figure 2. The considered scheme for taking into account the influence of deep laying tubing: a – to dynamic impact; b – after dynamic influence

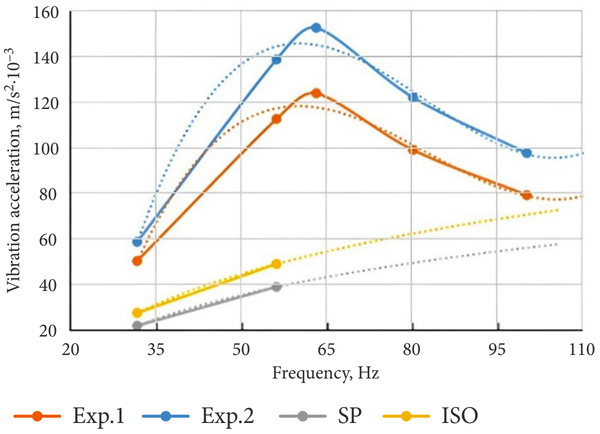


Figure 3. Acceleration at point A (shallow laying "Exp.1" and deep laying "Exp.2")

Table 2. Vibration acceleration according to different regulatory documents

Name of the normative document	Vibration acceleration, $m/s^2 \cdot 10^{-3}$	
	31.5 Hz	63 Hz
CH 2.2.4/2.1.8.566	22	45
ISO_ 4866	27.6	49.06
Result of experiment No. 1	50.38	112.55
Result of experiment No. 2	58.72	138.62

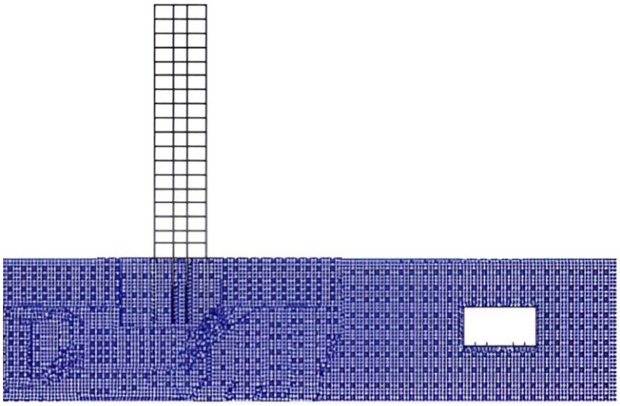


Figure 4. Calculation scheme of an office building with real characteristics of soils in LIRA SAPR

The calculation was made in LIRA-SAPR with the consideration and implementation of the direct integration method of the motion equations. This is an iterative step-by-step method that allows one to obtain the parametric parts of the stress-strain state of structures at any time, taking into account the nonlinearity. The soil is modeled by flat, physically non-linear universal finite elements. The influence of shallow laying underground tubing with a frequency of passing the rolling stock $t = 8$ s is investigated. The soil parameters taken for the test task are summarized in Table 3.

The results of the calculations are presented in the form of a comparative table (Table 4), which shows the numerical values of the change in forces at the control points (columns of the 1st and last floor) of the metal and reinforced concrete structures under vibration exposure from the movement of the metro. The minimum, maximum and arithmetic mean values of efforts for the indicated period of the subway vibrodynamics influence are obtained.

Figures 5 and 6 show comparative diagrams of changes in the internal forces M, N, Q of the reinforced concrete and metal frame in the columns of the 1st and last floors.

Basing on numerous studies, it can be concluded that the metal frame better perceives dynamic loads from the underground rolling stock (Banakh, 2011a).

The most exposed from dynamic loads are the upper floors of the building, while the floors of the lower floors of the building do not have a significant response spectrum to frequencies in the range above 20 Hz, and the ceilings of the upper floors of the building respond to the 35–45 Hz spectrum at a higher frequency and are also able to resonate. The frequencies at which the study took place are shown in the Table 5. Standard deviations are taken into account by LIRA-SAPR.

The next stage of the experiment is the metal frame behavior study; metal frame of the same building of the retail and office complex, for different vibration frequencies (Table 4), which are recommended for calculation in the regulatory documents SP 23-105-2004, as well as for frequencies that can cause parametric resonance in rod systems (Bashinsky & Barabash, 2012). Checkpoints are shown in Figure 7.

Table 3. Soil characteristics

Soil	E, t/m^2	V	H, cm	R_0, t/m^2	C, t/m^2	R_t, t/m^2	F_i	K_e
Sandy loam, hard	1020	0.35	800	1.55	0.5	0.1	16	5
Fine sands	4070	0.3	800	1.99	0.8	0.16	22	5
Plastic loams	810	0.35	800	1.82	5	1	16	5
Fine sands, permeable	4580	0.3	800	2.05	1	0	10	5
Sands of medium size	3560	0.3	800	1.95	1	0	10	5
Soft-plastic loams	910	0.35	800	1.85	1	0	10	5

Table 4. Force indications M, N, Q in reinforced concrete columns

Value	Element	M, kN·m	N, kN	Q, kN
Min	Column of the 1st floor metal structure	8.62	–302.37	6.26
Mean		8.91	–301.41	6.49
Max		9.18	–300.73	6.71
Min	Column of the 1st floor of reinforced concrete structure	5.36	–379.34	3.26
Mean		5.55	–378.99	3.38
Max		5.71	–378.62	3.49
Min	Column of the last floor metal structure	12.00	–16.10	8.16
Mean		12.09	–15.91	8.17
Max		12.19	–15.73	8.19
Min	Column of the last floor of reinforced concrete structure	15.29	–19.33	10.56
Mean		15.38	–19.16	10.70
Max		15.45	–18.98	10.82

Table 5. Frequency characteristics

Frequency, Hz	Radian
5.5	34.54
11	69.08
16	10048
31.5	197.82
63	395.64

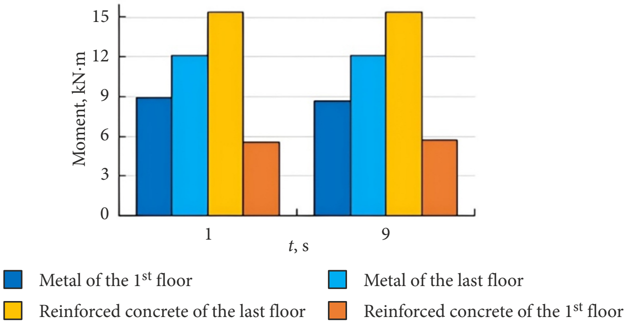


Figure 5. Internal bending moments M in the columns of the 1st and last floor of the reinforced concrete and metal frame

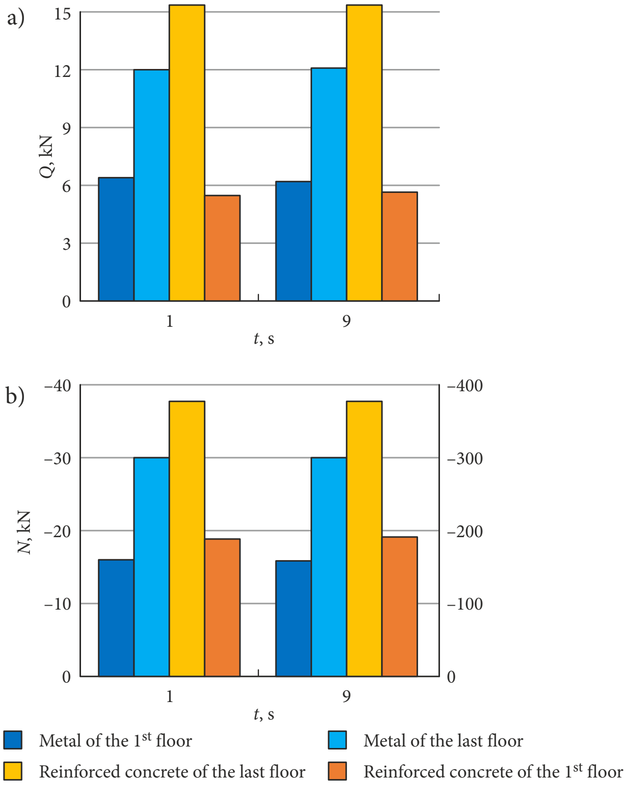


Figure 6. Internal forces a – Q and b – N in the columns of the 1st (N axis –400..0) and the last floor of the reinforced concrete and metal frame

Table 6 shows the peak displacements, accelerations, and speed in the X direction for each checkpoint shown in the scheme above. The authors conducted a structural analysis of frequencies close to the dynamic impacts from the metro rolling stock to obtain these data. At all points, the maximum peaks appeared at a low frequency of 5.5 Hz, and the extremes of vibration velocity and vibration acceleration were found at a frequency of 16 Hz. These frequencies can be attributed to the resonant zone closest of floor vibrations, which explains the extreme increase in the amplitude of floor slabs vertical vibrations.

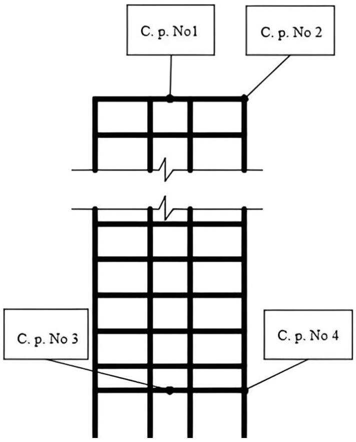


Figure 7. Scheme of checkpoint layout

Table 6. Dynamic properties at checkpoints of the structure according to the LIRA SAPR calculations

Frequency, Hz	Peak displacements in the X direction, μm	Max speed, mm/s	Max acceleration, mm/s^2
Point No. 1			
5.5	1019.948	2.79	86.55307
11	1019.939	0.4265	7.8705
16	1019.94	0.984357	79.05343
31.5	1019.94	0.096619	2.635536
63	1019.939	0.071887	1.560345
Point No. 2			
5.5	1019.156	2.616316	84.79664
11	1019.147	1.41	86.041
16	1019.149	1.16824	93.7096
31.5	1019.148	0.110694	4.307166
63	1019.148	0.06903	2.043142
Point No. 3			
5.5	196.5235	9.844534	330.1593
11	196.2538	0.734456	42.9981
16	196.2294	0.380801	21.33064
31.5	196.2224	0.142559	5.641929
63	196.2193	0.090671	3.437784
Point No. 4			
5.5	196.528	9.59996	316.0826
11	196.2641	0.75803	45.2817
16	196.2871	3.0487	148.7543
31.5	196.2349	0.154642	6.467091
63	196.2319	0.093919	4.887758

Acceleration and speed graphs at control points were built in the program, and we saw that the greatest reactions of structures at control points occur at low frequencies from 5.5 and gradually fade to 31.5 Hz, as well as maximum. peaks at 16 Hz, at points on the top floor of the building. The speed graph is shown in Figure 8.

The acceleration graph is shown in Figure 9.

Numerous conducted studies make it possible to conclude that the metal frame withstands dynamic loads from the metro rolling stock better. The upper floors of the building are most susceptible to impact from dynamic loads. Lower floor slabbing of buildings does not have a significant response spectrum to frequencies of above 20 Hz, but upper floor slabbing reacts to the high-frequency spectrum of 35–45 Hz and can even resonate (Table 7).

The largest reactions from the impact of dynamic loads occur on the upper floors of the building. Ceilings located on the lower floors of the building naturally reduce the response to the vibrational frequency range. The upper floors and other load-bearing parts of the building not only react to the high-frequency range of operating frequencies, but can also cause their own vibrations and even resonance. Accordingly, the superposition regularity of building natural vibrational frequencies, especially high-altitude ones (since the bending moment of the building increases with the vertical length) with the frequencies transmitted by the soil from the subway tubing was detected (Kulyabko, 2010).

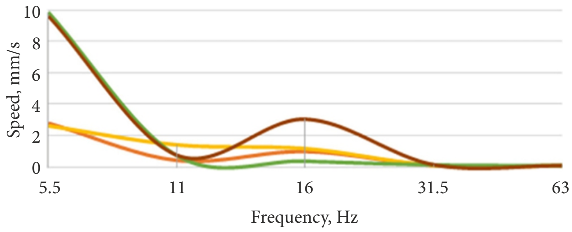


Figure 8. Speed at control points (mm/s)

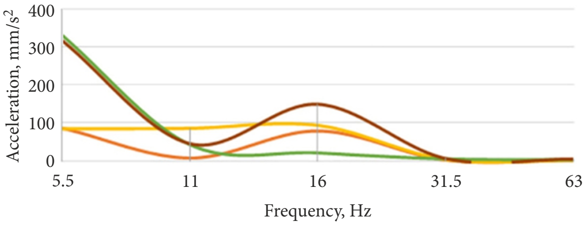


Figure 9. Acceleration at control points mm/s^2

Table 7. Frequencies on which studies were conducted

Octave with a geometric mean frequency, Hz	Radian
5.5	34.54
11	69.08
16	100.48
31.5	197.82
63	395.64

This dynamic response feature of high-rise buildings structural elements should be considered before the design loads of a building under construction begin, using additional reinforcement methods, and also the use of materials in the load-bearing buildings structures, which not only can be less subjected to dynamic loads, but have the ability to extinguish them too. The authors developed an algorithm for a more detailed study of loads. This calculation algorithm is presented below:

1. A designed scheme of the building was formed, and further calculation was performed for a given influence in a linear formulation. Its results determined the following: the values of concentrated masses in elevation; frequency and period of natural vibrations; ordinates of natural modes of vibrations; the magnitude of the inertial forces in elevation. Furthermore, the structural analysis was conducted, and areas of working and structural reinforcement for reinforced concrete structures were selected.
2. A numerical model of soil was developed based on geological examination. The dynamic characteristics of the soil were modeled using finite elements 281–284, namely the physically nonlinear rectangular, triangular, and universal rectangular finite elements of the plane stress problem. This finite element was designed to stimulate one-way compression strain of soil; it considered the displacement according to the plain deformation scheme according to the Coulomb's law.
3. The linear design scheme was then transformed into a physically nonlinear model (Figure 10). The Rayleigh coefficients were determined and set for construction materials and soils in order to consider the damping effect. Boundary finite elements (FE-67) in the model of the foundation created boundless soil mass. This FE is intended for modeling a flat boundless soil mass located outside the design scheme. The author implemented this function to prevent the reflection effect when limiting conditions were applied to the soil.
4. The load history of the design scheme was formed, which sequentially included a full vertical load. Horizontal dynamic forces were applied step by step. The total dynamic impacts in the system were formed from the coordinated mass matrix of static effects using the DYNAMICS PLUS module in the LIRA-SAPR software package.
5. The DYNAMICS IN TIME module was used to consider the influence of the time factor on the propagation of vibrodynamic fluctuations (Figure 11).

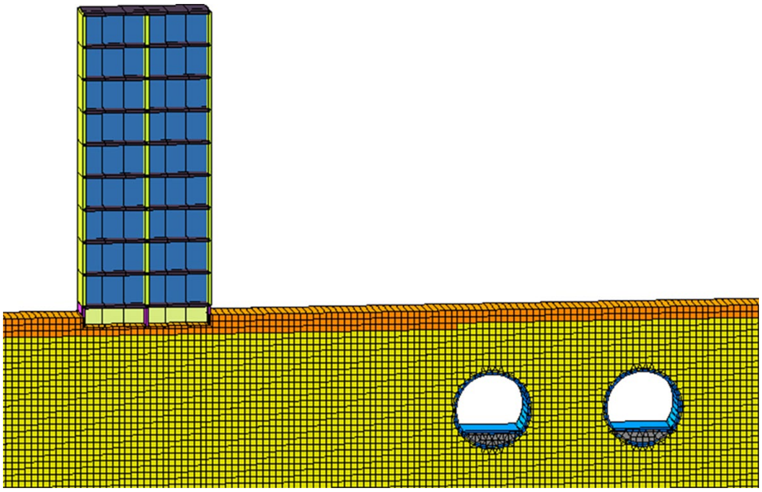
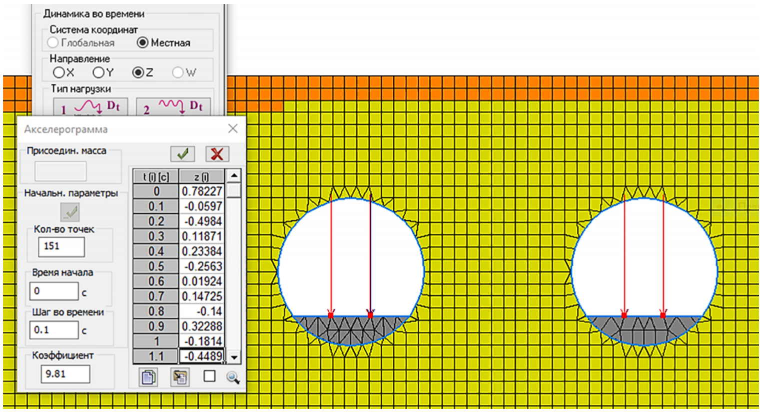


Figure 10. The design scheme of a panel residential building near the metro of shallow laying



Динамика во времени

Система координат: ○ Глобальная ● Местная

Направление: ○X ○Y ●Z ○W

Тип нагрузки

Акселерограмма

Присоедин. масса

Начальн. параметры

Кол-во точек: 151

Время начала: 0 с

Шаг во времени: 0.1 с

Коэффициент: 9.81

t (i) [c]	z (i)
0	0.78227
0.1	-0.0597
0.2	-0.4984
0.3	0.11871
0.4	0.23384
0.5	-0.2563
0.6	0.01924
0.7	0.14725
0.8	-0.14
0.9	0.32288
1	-0.1814
1.1	-0.4489

Figure 11. The design of the load caused by the metro in the DYNAMICS IN TIME module in LIRA-SAPR

Loads were modeled using a graph of dynamic vibration accelerations generalized over the entire frequency range. The authors set an accelerogram of actions, based on which a small number of moments were obtained, and results would be generated for each of them.

As a result of the calculation, it was possible to determine the displacements, speeds, and accelerations of the nodes and the forces and stresses in the load-bearing structures, calculated at all given points in time (Figures 12, 13).

The analysis of the graphs of the results of displacements, speeds, and accelerations at the control points of the building indicates that the authors' method of calculations makes it possible to bring the results closer to the experimental data. According to the graph, displacements become more frequent at control points, especially at the top of the building. The above is caused by resonance phenomena that appear and bring their own fluctuations in the structure. The authors' method of calculation considers a larger number of parameters that affect the nature of the deformation of load-bearing structures.

3. Discussion

The level of tunnel structures vibrations depends on many factors: the type of rolling stock, the trains speed, their workload, the tunnel rim and tracks structures type, the method of laying rails, and so on. As a rule, the frequency spectrum of fluctuations in the movement of metro trains is in the range of low and medium frequencies. It is known that the spectrum of vibration displacement is more pronounced in the low-frequency region, but after trial measurements on the earth's surface, a low level of this

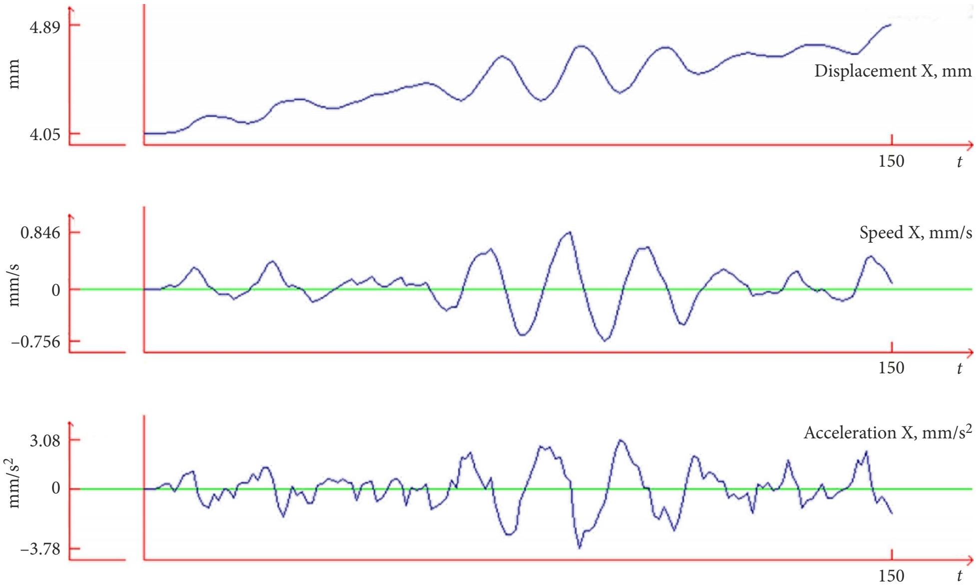


Figure 12. Graphs of calculation results at the control point on the first floor along the X axis

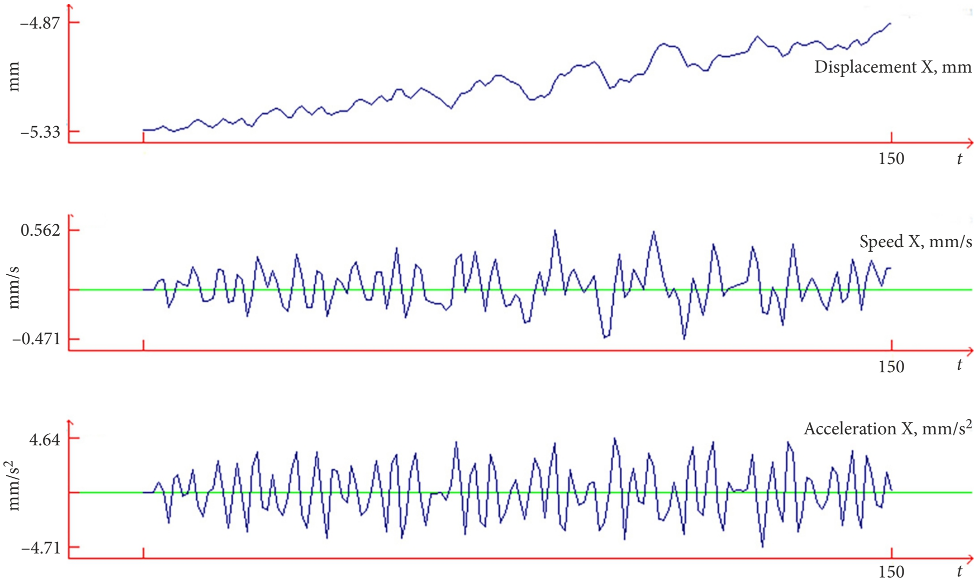


Figure 13. Graphs of calculation results at the control point on the fourth floor along the X axis

indicator was found, at the level of the device's own noise. The level of vibration velocity reflects the transfer of vibrational energy by waves, and the vibration-accelerating force. When assessing the vibration of the soil and building structures, a sensor sensitive to vibration acceleration should be used (Antonovskaya et al., 2010; Sushchev et al., 2009). Vibration acceleration value in dB in octave bands and broadband spectrum) was chosen as the main vibration measurement parameter.

Also, the assessment of vibration in the metro tunnel was carried out and the levels of vibration velocity of vertical and horizontal vibrations were chosen as the measured and analyzed value. The most effective way of vibration instrumental assessment is spectral analysis, which is performed using a digital analyzer, which makes it possible to represent a complex oscillatory process through the sum of simple sinusoidal oscillations (harmonicas). The spectral analysis of vibration oscillations is carried out using electrical filters with a bandwidth equal to one octave or 1/3 octave. When evaluating vibration as a physical process, it is sufficient to know the frequency response of one of the three quantities: displacement, velocity or acceleration, which are taken to be absolutely equal.

Therefore, in the study of the soil and building structures vibrations, the digital analyzer of the mechanical vibration spectrum "DC-2111" with the corresponding sensor "Brüel and Kjær-4370" was used as the main instrument. To check the correctness of the obtained indicators, an Oktava-101A digital octave vibrometer with a sensor was additionally used. "Global test – AR". The devices were certified by the State Enterprise All-Ukrainian State Research and Production Center for Standardization of Metrology, Certification and Consumer Rights Protection Ukrmetrteststandart. Before the measurements, the corresponding equipment was calibrated.

To determine the vibration levels of the metro, the nature of the impact and its duration, full-scale acoustic measurements were made using equipment from Brüel and Kjær:

1. Portable modular analyzer of acoustic and vibration signals in real time, type 2260N-002;
2. Vibration transducer, type 752A12 (vibration sensor);
3. Portable vibration calibrator, type 4294.

Vibration from railway transport is transmitted through the rail tracks to their resistance and further into the ground. Nearby buildings are subject to loads that affect their technical condition, the condition of the foundations and the soil mass on which they are located. Taking into account the widespread physical deterioration of existing buildings, especially architectural monuments that cannot be destroyed or disposed of during modernization, the issues of ensuring the reliability of structures associated with vibrodynamic loads are becoming increasingly relevant.

Considering the experimental part of the study, we see an instrumental study of the vibrational dynamic oscillations level from the action of a shallow underground, on buildings that have been in operation for a certain time and are in the zone of influence of long-term dynamic vibration loads (Assimaki et al., 2005). The objects to be studied are typical for many city districts (they were selected according to average urban planning indicators), since both tram lines and the metro have a significant length within dense urban development, as well as located in the central part of the city. Unfortunately, there are no national standards yet that regulate the conduct of empirical experiments to measure vibration from specific known systems and evaluate their impact on buildings and structures, so the empirical studies were carried out in accordance with the standards (Ministry of Regional Development of Ukraine, 2005).

The algorithm and methodology for conducting a natural experiment were as follows:

1. Installation of sensors on the ground and building structure surface;
2. Recording parameters (frequency spectrum and vibration acceleration indicators);
3. Processing and analysis of the received data.

To determine the parameters of soil vibration between the buildings and the tunnel, the sensors were installed on a special metal pin, which was immersed in the ground. In the living quarters of the apartments, the sensors were installed on the floor in accordance with MR 2957-84. In the basements, the sensors were installed on the walls closest to the metro line. At each point, vibration acceleration was measured in three orthogonal directions along the "X", "Y" axes (horizontal vibration) and along the "Z" axis (vertical vibration). The "X" axis is perpendicular to the tunnel axis, the "Y" axis is parallel to the tunnel axis. The results were compared with the normative values in the direction where the maximum values were recorded, namely along the "Z" axis (vertical vibration).

During the tests, it was found that in some cases the vibration value significantly (up to 10 dB at night time) exceeds the values specified in the regulatory sources (Ministry of Regional Development of Ukraine, 1996). Vibrations were also tested directly in the metro (in its tunnel) to get a more complete picture.

For natural measurements in the metro tunnels, special embedded parts in the form of metal platforms were prepared and concreted. Embedded parts were installed on the tray and tubing along the right and left paths and clearly regulated the installation locations of vibration sensors on the tunnel structures.

For measurements in the metro tunnel, the most loaded periods during the day were selected, when the loads corresponded to the maximum peak – in the morning, from 8:00 to 9:00, and in the evening – from 18:00 to 19:00.

Vibration velocity was measured in real time in a narrow-band frequency range, followed by a detailed analysis and computer processing of the measurement results. Vibration levels were assessed while passing opposite the measurement point of 20 metro trains in accordance with the traffic schedule, the filling of cars and their technical equipment. Taking into account the orthogonal coordinate system and the results of preliminary measurements of the metro vibration level for acoustic measurements, vibrations were selected that affect the tunnel structure in the vertical (perpendicular to the supporting surface) direction – the Z axis and the horizontal one – the Y axis. As a result of the vibroacoustic measurements, the levels of vibration velocities were obtained under the rail, on the tray and on the tunnel processing during the movement of metro trains, on ordinary rails and on blocks passing along the vibration-proof track.

For each section of the track, the vertical and horizontal levels of vibration velocity, dB, were determined in 1/3-octave bands of geometric mean frequencies (from 2 to 100 Hz). Figure 14 shows the average levels of vibration velocity, dB; in 1/3 octave bands with geometric mean frequencies from 2 to 100 Hz.

The obtained results of dynamic vibration acceleration are set in the form of an accelerogram of the load (Figure 15) on the rail in LIRA-SAPR, the module "Dynamics PLUS".

The analysis of the graphs of the results of displacements, speeds, and accelerations at the control points of the building indicates that the authors' method of calculations makes it possible to bring the results closer to the experimental data. According to the graph, displacements become more frequent at control points, especially at the top of the building. The above is caused by resonance phenomena that appear and bring their own fluctuations in the structure. The authors' method of calculation considers a larger number of parameters that affect the nature of the deformation of load-bearing structures.

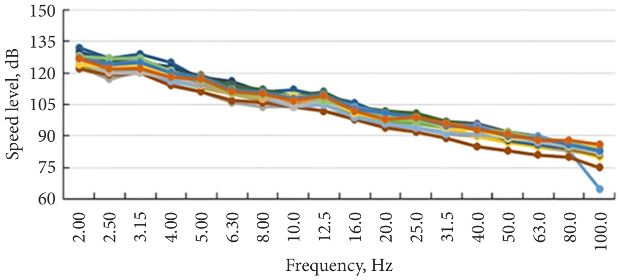


Figure 14. Average levels of vibration velocity, dB; in 1/3 octave bands with geometric mean frequencies from 2 to 100 Hz

Conclusions

Theoretical studies of the stress-strain state of building structures under vibrodynamic effects of the metro have been carried out. It is shown that the metro influence on the structures of buildings is significant and differs significantly from the impact of seismic loads by the nature of the influence.

A method has been developed that most accurately reflects the operation of the structure during the vibrodynamic effects of the metro. This makes it possible to carry out correct numerical calculations and take into account this effect on the supporting structures of the building and constructions, including preliminary deformations. An algorithm for calculating the structures of buildings under the action of vibrodynamic effects is proposed using the refined calculation methodology, the method of finished elements and the methodology implemented with the help of BIM technologies.

A technique for conducting full-scale measurements of the vibrodynamic effects parameters created by the metro movement using a vibrometer has been developed. Field measurements of the values of vibration acceleration of the soil and assessment of the vibration impact from the mobile rail transport have been carried out, and the maximum values of vibration accelerations during the metro movement have been obtained.

To develop a computer model of an object adequate to real conditions using BIM technologies, located near the shallow and deep laying subway lines, considering the vibrations influence propagating on the supporting structures of the building, it is necessary to conduct a complex of structures strength studies under prolonged exposure to vibrodynamic loads.

An assessment of the metro depth influence and the distance from the source of vibrations to the building was made, and a calculation method was created taking into account these factors. The reliability of the proposed method is confirmed by comparison with experimental data. The complex problem of determining the vibrodynamic impact intensity of the subway on the construction object structures has been solved. Verification of the developed technique was carried out based on comparison of the numerical experiments results with the full-scale vibration surveys outcome.

A closeness of natural bending vibration frequencies of high forms of high-rise buildings and natural heave

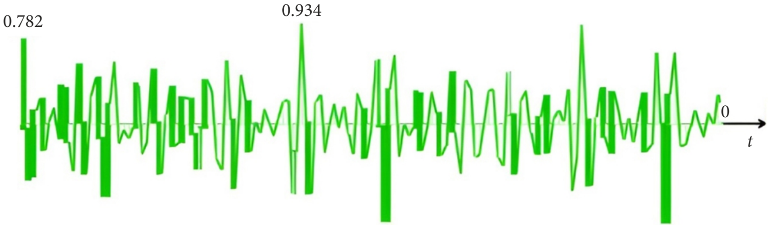


Figure 15. Setting the load from the metro in the module "Dynamics in time" in PC LIRA SAPR

vibration frequencies of upper floor slabbing is observed under vibrodynamic impact from the moving metro rolling stock. One should consider this feature of the dynamic responses of structural elements of high-rise buildings before the construction work and take additional protective measures. It is also important to use materials for load-bearing structures of buildings that are less susceptible to the impact of dynamic loads. The developed technique allows authors to reduce the volume and costs of experimental research by up to 30%, speed up the process of preliminary analysis (compared to experimental research), focus attention on problem areas (soils and foundations of buildings), and make a preliminary conclusion about the possibility of construction on the selected construction site.

The developed technique of numerical calculations is universal; it helps to study buildings with different types of structures, which significantly increases the reliability of the project design of a building susceptible to external vibrations. The vibration levels of reinforced concrete structures caused by moving metro trains change significantly (up to 25%) depending on different trains (their load, in-service time, etc.). The highest levels of vibration acceleration of the floor slab were obtained for vertical vibration; their frequency ranged from 16 to 80 Hz and generally exceeded the value in other directions, in some cases by almost 40 dB. The analysis shows that correct assessment and consideration of the influence of vibrations eliminates various undesirable situations and can provide a significant economic effect when developing urban areas near the metro.

Algorithms have been implemented that allows to calculate the vibrodynamic effects of the metro, considering the time factor. Numerous calculations and experimental studies of the building have shown the parameters similarity. Practical recommendations have been developed for determining the stress-strain state of construction units of buildings and structures under the vibrodynamic effects of the subway, allowing to obtain preliminary data on the future behavior of building structures, and to draw a preliminary conclusion about the possibility of building on a correctly selected site.

Competing interests

The authors declare that they have no competing interests.

Funding

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