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MODELING OF THE SUBWAY DYNAMIC INFLUANCE ON THE GROUND STRUCTURE

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Abstract: The article discusses a new approach to modeling the behavior of structures under the influence of dynamic loads, including loads from ground and underground transport. The approach is to apply the direct integration method, as well as the SBFEM method to calculate the forces in load-bearing building structures under dynamic influences, taking into account a number of factors - the damping properties of the subgrade, physical nonlinearity of soils and the passage of waves in the soil space. The article presents the main theoretical premises, the results of a numerical experiment of a real monolithic building, built in the zone of influence of the subway.

Keywords: dynamic influences, finite elements, structural modeling, internal forces, vibration acceleration, vibration velocity, subway, vibration, soil, boundary conditions, design, dynamic characteristics, damping

МОДЕЛИРОВАНИЕ ДИНАМИЧЕСКОГО ВОЗДЕЙСТВИЯ МЕТРОПОЛИТЕНА НА НАЗЕМНОЕ СООРУЖЕНИЕ

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Аннотация: В статье рассматривается новый подход к моделированию поведения конструкций при влиянии динамических нагрузок, в том числе и нагрузок от наземного и подземного транспорта. Подход заключается в применении метода прямого интегрирования, а также метода SBFEM для вычисления усилий в несущих строительных конструкциях при динамических воздействиях с учетом ряда факторов - демпфирующих свойств грунтового основания, физической нелинейности грунтов и прохождения волн в грунтовом пространстве. В статье приводятся основные теоретические предпосылки, приводятся результаты численного эксперимента реального монолитного здания, построенного в зоне влияния метрополитена.

Ключевые слова: динамические воздействия, конечные элементы, моделирование конструкций, внутренние усилия, виброускорения, виброскорости, метрополитен, вибрация, грунт, граничные условия, проектирование, динамические характеристики, демпфирование

In recent decades, the world has experienced urbanization and intense urban growth. At the same time, in order to unload the traffic flow in cities, underground space is being developed and new metro lines are being built. However, the underground is a source of increased vibration and noise levels. As a rule, new tunnels are laid in the formed urban development, which causes an increase in vibration and noise in buildings and structures adjacent or located above metro lines, as well as new construction is carried out near existing metro stations and tunnels. Constantly acting vibration loads from the movement of the subway affect the physical and mechanical properties of soils and the bearing capacity of structures in operation, erected and reconstructed buildings and structures [1]. It is not possible to provide a complete and reliable assessment of these actions only by instrumental methods.

Therefore, it is very important to develop complex numerical modeling tools that will allow obtaining objective and comprehensive information about the actual stress-strain state (SSS) of load-bearing structures of buildings and structures under vibration effects. In the future, this will make it possible to develop a set of measures to counteract vibration effects in order to prevent damage and further destruction of structures.

The purpose

The purpose of the article is to assess the effect of vibration loads on the stress-strain state of the bearing structures of buildings and structures.

In addition, a methodology for modeling the behavior of buildings under the constant influence of the subway is presented.

Formulation of the problem

When designing buildings and structures of increased responsibility, regulatory documents regulate the calculation of the system "ground part - foundation - foundation" for dynamic effects. This problem can be solved by numerical modeling methods, which make it possible to take into account such factors as the damping properties of the subgrade, physical nonlinearity of soils and the passage of waves in an infinite half-space of the subgrade.

The development of new calculation methods for dynamic effects and the improvement of existing ones are especially important in the design of multi-storey buildings.

Direct integration of equations of motion (method of central differences)

Calculation under the influence of dynamic loads is based on solving differential equations:

$$M\ddot{\vec{u}}(t) + C\dot{\vec{u}}(t) + K\vec{u}(t) = \vec{q}(t) \qquad (1)$$

$$\vec{q}(t) = -\sum\nolimits_{i=1}^{3}\left(M\vec{v}_i u_g^i(t)\right) - \sum\nolimits_{i=4}^{6}\left(M\vec{v}_i u_g^i(t)\right) \qquad (2)$$

where M, C, K are – accordingly matrices of masses, damping and system stiffness respectively;

$\vec{u}(t), \dot{\vec{u}}(t), \ddot{\vec{u}}(t)$ are vectors of nodal displacements, velocities and accelerations at the moment of time *t*;

$\vec{q}(t)$ are loads corresponding to the moment in time *t*.

For accelerations at time t, using the method of central differences, we can write the expression in the following form:

$$\ddot{\vec{u}}(t) = \frac{\vec{u}(t+\Delta t) - 2\vec{u}(t) + \vec{u}(t-\Delta t)}{\Delta t^2} \qquad (3)$$

The calculation error by formula (3) is of the order of Δt^2, and the following expressions are used to calculate velocities and displacements with errors of the same order:

$$\dot{\vec{u}}(t) = \frac{\vec{u}(t+\Delta t) - \vec{u}(t-\Delta t)}{2\Delta t};$$
$$\vec{u}(t) = \frac{\vec{u}(t+\Delta t) + \vec{u}(t-\Delta t)}{2}. \qquad (4)$$

Substituting expressions (4) into expression (1) and determining the vector $\vec{u}(t+\Delta t) + \vec{u}(t-\Delta t)$, we obtain the following equation:

$$\left[\frac{2M}{\Delta t^2} + \frac{C}{\Delta t} + K\right]\left(\vec{u}(t+\Delta t) + \vec{u}(t-\Delta t)\right) =$$
$$= 2\left(q(t) + \frac{2M}{\Delta t^2}\vec{u}(t) + \frac{C}{\Delta t}\vec{u}(t-\Delta t)\right) \qquad (5)$$

In the process of performing the calculation, displacements at the control points of the building are determined with a gradual application of a dynamic load to the building:

$$\left[\frac{M}{\Delta t^2} + \frac{C}{2\Delta t} + \frac{K}{2}\right](u(t+\Delta t) =$$
$$= q(t) + \frac{2M}{\Delta t^2}u(t) - \qquad (6)$$
$$-\left[\frac{M}{\Delta t^2} - \frac{C}{2\Delta t} + \frac{K}{2}\right]u(t-\Delta t)$$

Obtained displacements $\bar{u}(t+\Delta t)$ can be determined taking in account previously found displacement $\bar{u}(t)$ and $\bar{u}(t-\Delta t)$ from equations (1,2).

After entering the initial parameters of the computational model and calculating the mass matrix, the subroutine for calculating the total vector of forces and the critical time step is launched. Based on the obtained vector, the calculation of nodal accelerations, velocities and displacements is carried out.

Damping factor accounting when calculating structures for dynamic effects

The damping matrix [C] in the Rayleigh model [2] is defined as a linear combination of the system stiffness matrix [K] and the system mass matrix [M]:

$$[C]=\beta[K]+\alpha[M] \tag{7}$$

where α is a mass proportionality factor (C-1);

β is a proportionality factor (C).

The orthogonal transformation of the damping matrix (7) brings the matrix [C] to the form:

$$2\xi_i\omega_i=\alpha+\beta\omega_i^2 \tag{8}$$

Let us divide (9) by and express the dependence of the damping coefficient on frequency in the form:

$$\xi_i=\frac{\alpha}{2\omega_i}+\frac{\beta\omega_i}{2} \tag{9}$$

In order to determine the Rayleigh coefficients, a modal analysis of the structure (or its part) is carried out and by specifying empirical damping coefficients for the material at the two lowest natural frequencies, the coefficients are determined by the formulas:

$$\alpha=\frac{2\xi_i\xi_j\omega_i\omega_j}{\xi_i\omega_i+\xi_j\omega_j},\ \beta=\frac{2\xi_i\xi_j}{\xi_i\omega_i+\xi_j\omega_j}, \tag{10}$$

where $\omega_i\omega_j$ are natural frequencies;

$\xi_i\xi_j$ is a modal damping for the first and second natural modes, given as a percentage of the critical damping.

Modeling the passage of waves in an infinite half-space of a subgrade

There are two general approaches to solving this problem - the direct method and the subsystem method.

The inconsistency of the problem under consideration lies in the fact that the propagation of waves occurs in an infinite half-space, and a limited section of a soil half-space can be included in a specific calculation. Both methods differ in the boundary conditions imposed on the boundaries of the soil half-space. In the direct method, constraints are imposed on the boundaries of the selected area, which cause the reflection of waves and the return of energy. In order to reduce the influence of this negative factor, it is necessary to increase the size of the allocated area so that the waves reach the boundaries less than the time of the dynamic impact. This technique is ineffective, since it requires a significant increase in the time of the problem being solved, especially for three-dimensional problems.

In the subsystem method, two parts working together are modeled as two substructures, which are separated by a generalized interaction line. One part includes a building and a foundation with additional boundary conditions, this part can have non-linearity in both structure models and soil models. The other part includes the rest of the soil, which stretches indefinitely (Fig. 1).

The combination of the two subsystems is carried out using the interaction vector $r_b(t)$ acting in both directions - on the building and on the soil massif. The interaction vector in the direct dynamic problem is represented as a convolution vector:

$$r_b(t)=\int_0^t M_b^{\infty}(t)\{\ddot{u}(t-\tau)\}d\tau, \tag{11}$$

where $M_b^{\infty}(t)$ is acceleration response matrix. Index b denotes nodes lying on the interaction line, which belong to both the structure and the ground.

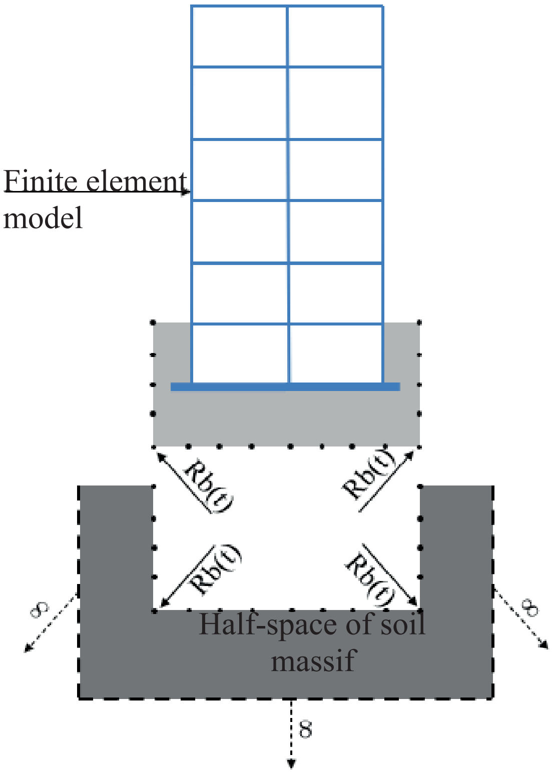


Figure 1. Schematic representation of the subsystem method

The equations of motion in the problem of integration in time can be written as:

$$\begin{bmatrix} M_{ss} & M_{sb} \\ M_{bs} & M_{bb} \end{bmatrix} \begin{Bmatrix} \ddot{u}_s(t) \\ \ddot{u}_b(t) \end{Bmatrix} + \begin{bmatrix} C_{ss} & C_{sb} \\ C_{bs} & C_{bb} \end{bmatrix} \begin{Bmatrix} \dot{u}_s(t) \\ \dot{u}_b(t) \end{Bmatrix} + \\ + \begin{bmatrix} K_{ss} & K_{sb} \\ K_{bs} & K_{bb} \end{bmatrix} \begin{Bmatrix} u_s(t) \\ u_b(t) \end{Bmatrix} = \begin{Bmatrix} p_s(t) \\ p_b(t) \end{Bmatrix} - \begin{Bmatrix} 0 \\ r_b(t) \end{Bmatrix} \qquad (12)$$

where K, C and M are matrices of stiffness, damping and mass of the structure, respectively, $\dot{u}(t)$ and $\ddot{u}(t)$ are vectors of displacements, velocities and accelerations;

$p(t)$ is vector of forces that act directly on the structure. The index s denotes the nodes belonging to the structure. To solve this equation, you need to know the vector of forces of interaction between the soil and the structure $r_b(t)$. In other words, you need to define the acceleration response matrix $M_b^{\infty}(t)$.

Equation of SBFEM [3] takes the form:

$$\int_0^t [m^{\infty}(\tau - t)][m^{\infty}(\tau)]d\tau + \\ + t\int_0^t [m^{\infty}(\tau)]d\tau + [e^1]\int_0^t\int_0^{\tau} [m^{\infty}(\tau)]dtd\tau + \\ + [e^1]^T \int_0^t\int_0^{\tau} [m^{\infty}(\tau)]dtd\tau - \frac{t^3}{6}[e^2]H(t) - t[m^0]H(t) = 0, \qquad (13)$$

where H(t) is Heaviside function

$$[m^{\infty}(t)]] = ([U]^{-1})^T [M^{\infty}(t)]([U]^{-1}) \qquad (14)$$

Methodology for the formation of calculation schemes in which there are limitless areas

The finite element design scheme of a limited part of the model is formed according to standard rules (limited subsystem).

No boundary conditions are imposed on the bounded subsystem. Both the structure model and the foundation model can have linear and physically non-linear elements. There may be additional links in a limited subsystem.

Next, a finite element diagram of the unlimited part of the model is formed. To do this, along the line of delimitation of the limited and unlimited parts, finite elements are installed, with the help of which infinity is modeled. Depending on the type of system, these can be two-node, three-node, or four-node elements. In the LIRA-SAPR software package, these are finite elements FE - 67, FE - 68 and FE - 69.

Then the system loads are simulated. The load can only be applied to a limited subsystem. The load can be static or dynamic.

Further work - the calculation and analysis of the calculation results are carried out according to the usual scheme.

Algorithm for assessing the dynamic influence of the subway on the supporting structures

Fig. 2 shows a block diagram of the algorithm for assessing the dynamic influence of the subway on the supporting structures:

1. A computational model of the building is formed and its calculation for the given influences is carried out in a linear setting, as a result of which the following are determined: the values of the concentrated masses at each level along the height; frequency and period of natural oscillations; ordinates of natural vibration modes; the magnitude of inertial forces at each height level; and also the design calculation is performed, the areas of reinforcement for reinforced concrete structures are selected.
2. A numerical soil model is created based on geological survey data. The dynamic characteristics of the soil are modeled using finite elements (FE) 281-284, namely the physically nonlinear rectangular, triangular and universal rectangular FE of the plane problem (soil). This FE is designed to simulate the one-sided work of the soil in compression, taking into account shear according to the planar deformation scheme.
3. Further, the linear computational model is transformed into a physically nonlinear one. To take into account the effect of damping, the Rayleigh coefficients for materials of construction and soil are determined and set. Boundary finite elements FE-67 in the foundation model are set, creating an infinite soil mass. This type of FE is intended for modeling a flat endless soil massif located outside the design model. This function is implemented to prevent the effect of reflection when imposing boundary conditions on the ground and in accordance with the Mohr-Coulomb law. It is used in a nonlinear stepper processor for calculating mine workings and tunnel penetrations.
4. The loading history of the design model is formed, which sequentially includes full vertical load; horizontal dynamic forces are added step by step. General dynamic actions in the system are formed from the coordinated matrix of masses of static actions using the “Dynamics in time” module in the LIRA-SAPR software package.
5. To take into account the influence of the time factor on the propagation of vibrations, the "Dynamics in time" module is used. The load is modeled using a graph of dynamic vibration accelerations generalized over the entire frequency range. The accelerogram of actions, the step and the integration time are set, on the basis of which the minimum number of moments will be obtained, for each of which the results will be generated.

Numerical experiment in SP LIRA-SAPR

A number of numerical experiments have been carried out in the LIRA-SAPR software package [4]. They prove the reliability of the fact of the influence of the underground, both shallow and deep, on the supporting structures of various buildings and structures.

The article presents the results of one of the experiments - the calculation of a high-rise building on the influence of the shallow underground [5], taking into account the real geological situation using the PC "LIRA-SAPR". The preliminary assessment and analysis of the vibration effects of the subway on a high-rise building were carried out in a linear and non-linear formulation, as well as taking into account the modeling of the real work of the soil massif and unlimited FE.

For the numerical experiment, a 27-storey monolithic building was taken as a basis (Fig. 3), which is located near the Svyatoshino-Brovarskaya line of the Kiev metro, which is shallow. Concrete class C25 / 30, working reinforcement class A400C. The thickness of the monolithic floor is 200 mm, the thickness of the vertical supporting structures is 300 mm. The foundation is a solid monolithic reinforced concrete slab on a pile field.

The calculation was carried out taking into account wind and snow loads according to the construction area. Long-term and short-term loads on the floor slabs of typical floors, as well as the attic floor, are taken into account.

In the course of the study, a number of calculations were carried out taking into account the nonlinear properties of the soil, taking into account the different frequency ranges caused by the movement of trains.

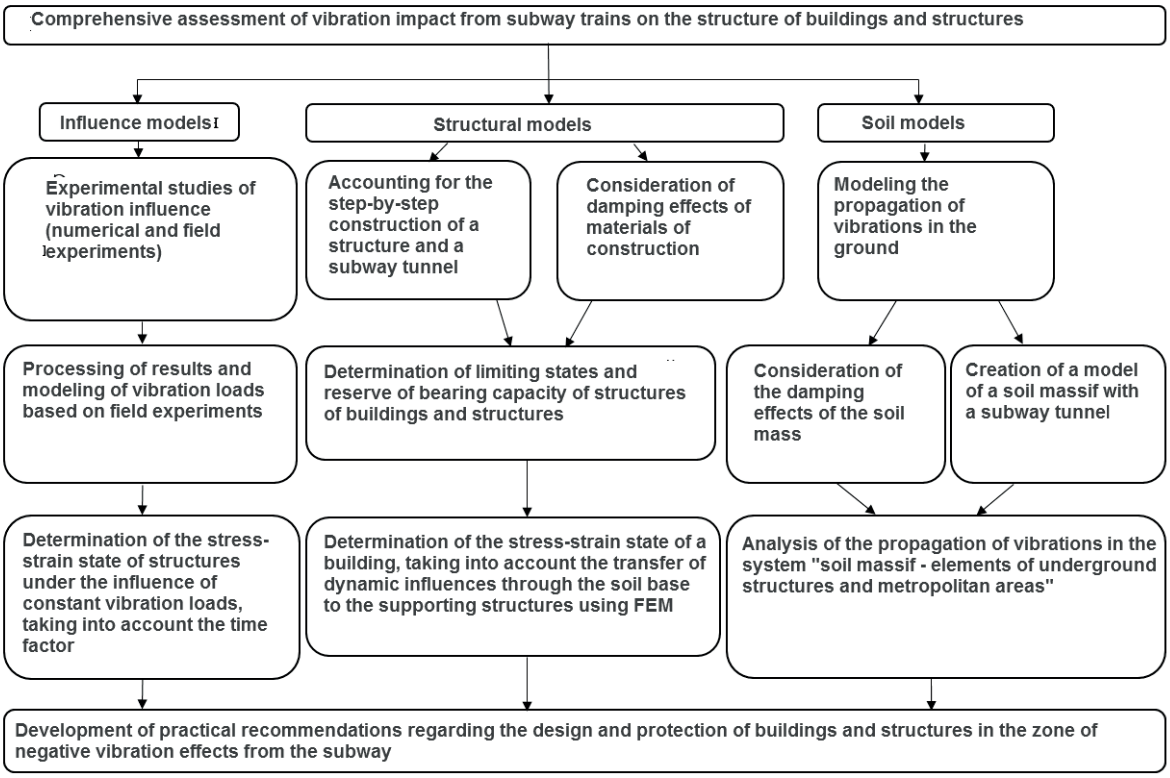


Figure 2. Algorithm for assessing vibration influence

The soil is modeled by flat, physically nonlinear finite elements. For the most accurate assessment of the vibration impact of the metro, we used sensor data from the measurement point, which was located directly at the base of the rail. The method of numerical simulation of dynamic loads in time in the LIRA-SAPR software package provides for setting the actions in the form of an accelerogram of vibration accelerations. For each moment in time, the equation is solved:

$$\sum_{n=0}^{i} a = A_i \sin(\omega_i \cdot t_n) + A_{i+1} \sin(\omega_{i+1} \cdot t_{n+1}) \qquad (15)$$

$$A_i = V_i \cdot \nu, \omega_i = 2\pi\nu \qquad (16)$$

where A_i *is* vibration acceleration, ω_i is cyclic frequency, which are calculated for each frequency from 2 Hz to 100 Hz - time point from 0 to 15 s, step 0.1 s.

The obtained results of dynamic vibration acceleration are set in the form of load accelerogram (Fig. 4) in the LIRA-SAPR software package.

Two types of models were investigated - a model with boundary conditions imposed along the perimeter of a limited soil massif (model 1) and a model using unlimited FE (model 2) [6].

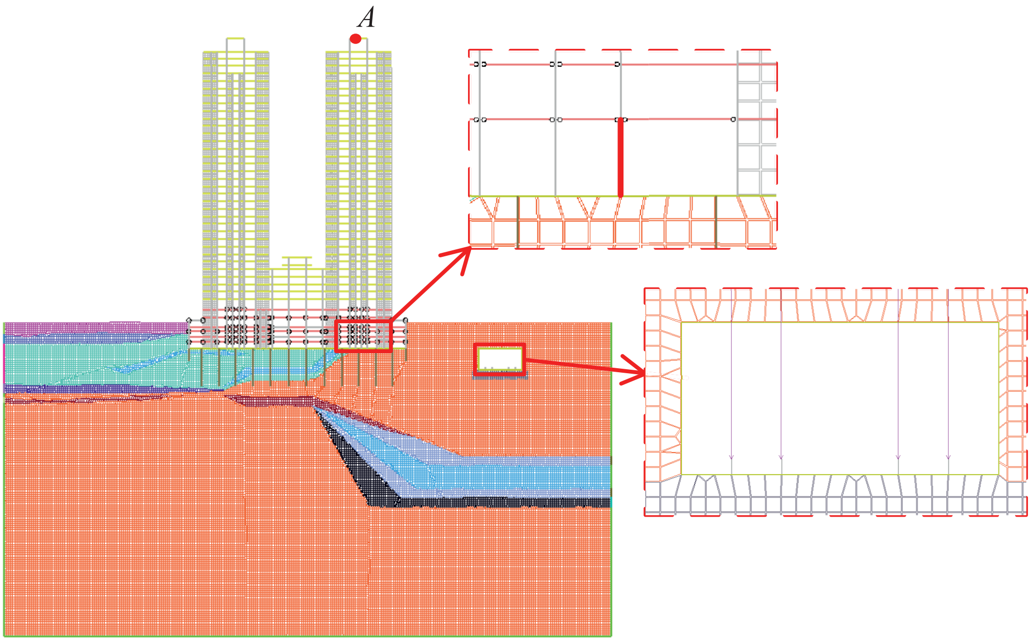


Figure 3. Design scheme of the building to take into account the dynamic influence of the underground

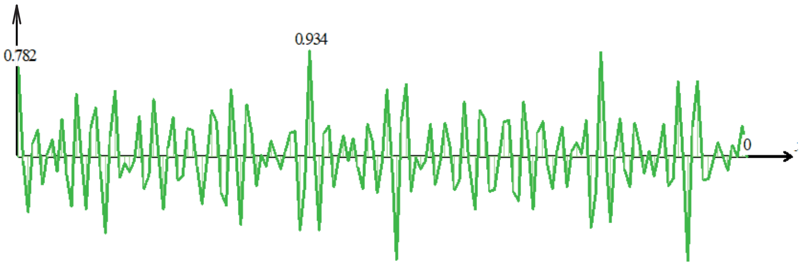
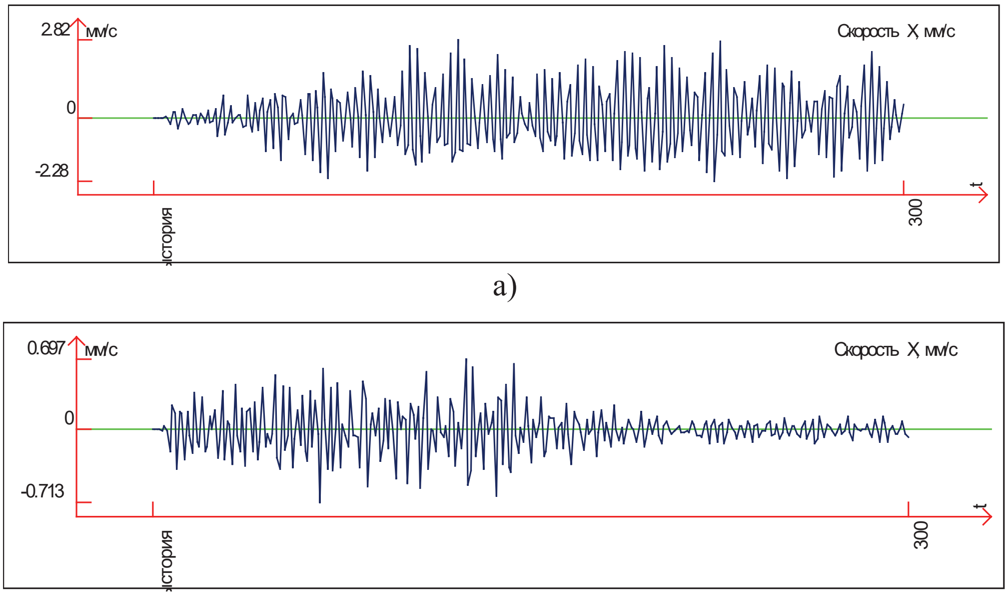


Figure 4. Specified accelerogram per metro track

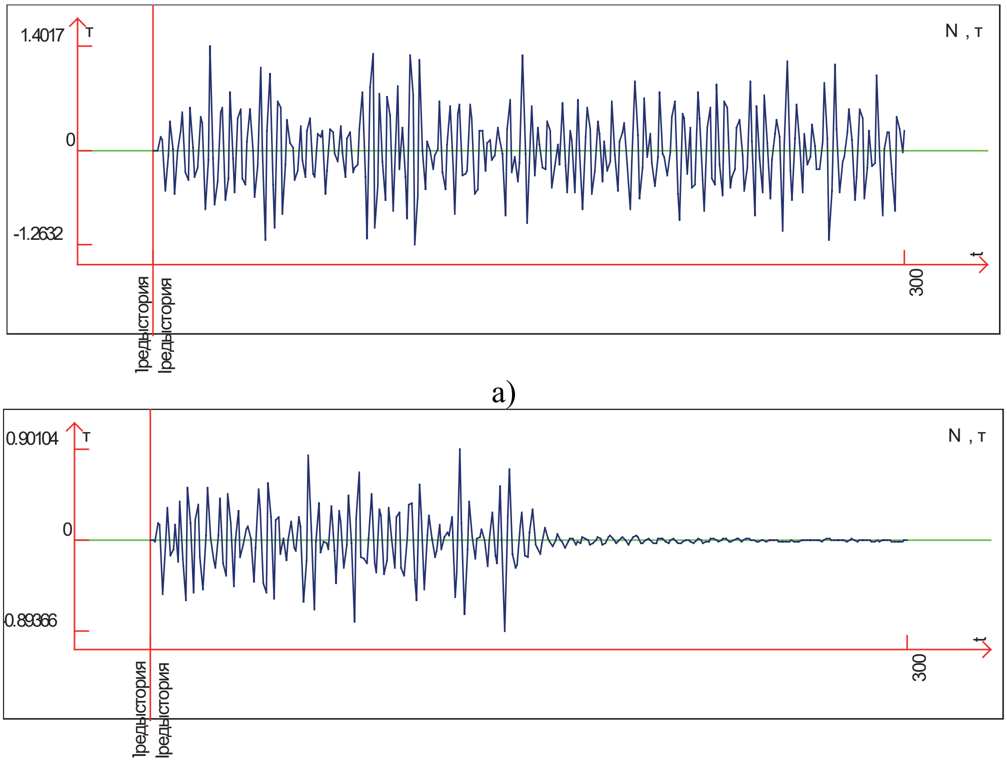


a)

b)

Figure 5. Vibration velocities at the control point (A) of the upper floor: a) model 1; b) model 2

Normative documents [7] regulate that the vibration load transmitted through the soil to the supporting structures of a building or structure (for example, when a track or metro station is located nearby) should not adversely affect the mechanical safety of the supporting and enclosing structures of a building during its life cycle. The estimated value, in accordance with Standard of RF GOST R 52892, is the peak value of the vibration velocity of vibrations at the control points. In our case, this is the top point of the building. The building in question belongs to the 2nd category of structures - “Residential buildings and buildings of similar design or purpose”. The limiting values of the peak vibration velocity of vibrations for such buildings is within 5 mm / s. For this numerical experiment, we see that the vibration velocities correspond to the normative ones. However, this is not always the case.



a)

b)

Figure 6. Longitudinal forces in the column from dynamic load: a) model 1; b) model 2

As a result of the calculation, data were obtained from which it can be seen, firstly, that the movement of the subway car creates vibration velocity and vibration acceleration at the control point on the top floor. And, secondly, we can track the damping of vibrations and dissipation of energy and, as a consequence, a decrease in internal forces in the column when using limitless ("transparent") FE, which we see in Figure 6.

Conclusions

A numerical modeling tool has been developed that allows one to assess the influence of the subway on building structures, taking into account many factors.

A method for numerical modeling of the processes of deformation and destruction of structures of buildings and structures under vibration influences of the underground has been developed and theoretically substantiated.

A mathematical and numerical model of vibration impact has been created, taking into account the time factor and the infinity of the soil mass.

A variant of modeling the system "source of vibration loads-soil-base-load-bearing structures of the building" is proposed.

A technique was proposed and implemented in SP LIRA-SAPR, which takes into account the continuous passage of a wave into an infinite region under dynamic influences.

The main recommendations are the use of damping devices in the construction of buildings in the zone of influence of the metro and the adoption of measures to reduce the level of penetrating vibration.

REFERENCES

1. **Clough R., Penziyen J.** Dinamika sooruzheniy [Dynamics of structures]: Translated from english. – Moscow: Stroyizdat, 1979. 320 p.
2. **Barabash M.S.** Manerial damping in dynamic analysis of structures (with LIRA-SAPR programm) / M. Barabash, B. Pisarevskyi, Y. Bashynskyi // Civil and Environmental Engineering, 2020. – Vol. 16, Issue 1, P. 63-70.
3. **Wolf, J.P.** and Song, C. (1996). Finite-Element Modelling of Unbounded Media, John Wiley & Sons Ltd, England
4. **Barabash M.S.** Komp'yuternoye modelirovaniye protsessov zhiznennogo tsikla ob"yektov stroitel'stva [Computer modeling of the life cycle processes of construction objects]: Monograph / Maria Sergeevna Barabash. – Kiyv: "Stal", 2014. – 301 p.
5. **Barabash M.S.** Stress-strain state of the structure in the service area of underground railway / M. Barabash, Ya. Bashinsky , A. Korjakins // IOP Conference Series: Materials Science and Engineering. The 3rd International Conference on Innovative Materials, Structures and Technologies (IMST 2017), 27–29 September 2017. – Riga, (Latvia), 2017. – Vol. 251. – conference 1.
6. **Gorodetskiy A.S.** Modelirovaniye raboty gruntovykh massivov na dinamicheskoye vozdeystviye [Modeling of work of soil massifs on dynamic impact] / A. S. Gorodetskiy, A. V. Pikul', B.YU. Pisarevskiy // International Journal for Computational Civil and Structural Engineering. – 2017. – Vol. 13. – Issue 3. – P.34–41.
7. Building Code of RF SP 465.1325800.2019 Buildings and structures. Protection against vibration of underground lines. Design rules. – [Introduced from 03-06-2020]. – Moscow: Standartinform, 2020. – 40 p.

СПИСОК ЛИТЕРАТУРЫ

1. **Клаф Р., Пензиен Дж**. Динамика сооружений: Пер. с англ. – М.: Стройиздат, 1979. – 320 с.
2. **Barabash M.S.** Manerial damping in dynamic analysis of structures (with LIRA-SAPR programm) / M. Barabash, B. Pisarevskyi, Y. Bashynskyi // Civil and Environmental Engineering, 2020. – Vol. 16, Issue 1, P. 63-70.
3. **Wolf, J.P. and Song, C.** (1996). Finite-Element Modelling of Unbounded Media, John Wiley & Sons Ltd, England
4. **Барабаш М.С.** Компьютерное моделирование процессов жизненного цикла объектов строительства: Монография / Мария Сергеевна Барабаш. – К.: «Сталь», 2014. – 301 с
5. **Barabash M.S.** Stress-strain state of the structure in the service area of underground railway / M. Barabash, Ya. Bashinsky, A. Korjakins // IOP Conference Series: Materials Science and Engineering. The 3rd International Conference on Innovative Materials, Structures and Technologies (IMST 2017), 27–29 September 2017. – Riga, (Latvia), 2017. – Vol. 251. – conference 1.
6. **Городецкий А.С.** Моделирование работы грунтовых массивов на динамическое воз-

действие / А.С. Городецкий, А.В. Пикуль, Б.Ю. Писаревский // International Journal for Computational Civil and Structural Engineering. – 2017.– Vol. 13. – Issue 3. – P. 34–41.

7. Здания и сооружения. Защита от вибрации метрополитена. Правила проектирования: СП 465.1325800.2019. – [Введен в действие с 03-06-2020]. – М: Стандартинформ, 2020. – 40 с. (Свод правил).

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