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ANALYSIS OF THE DYNAMIC BEHAVIOR OF A FRAME BUILDING CONSIDERING THE MULTILAYERED NATURE OF THE SOIL FOUNDATION

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Abstract. The influence of rolling stock loading on a twenty-three-story frame building located near the movement of railway trains in an urban area was investigated. Mathematical modeling of the dynamic behavior of multi-story buildings subjected to rolling stock loading was performed using a two-stage numerical method.

In the first stage, a finite element model of the multilayer soil foundation along with the ballast prism was created in the NASTRAN software complex, represented as a planar elastoplastic half-space with a length of 200 m and a depth of 30 m. A real geological cross-section consisting of five layers with different physical characteristics was used. The rolling stock load is represented as a vertical periodic excitation, concentrated at the center of mass of the system consisting of the bogie frame, the wheelsets of a freight wagon, and the ballast prism.

Modal analysis of the soil foundation and the ballast prism was performed using the Lanczos method. The influence of rolling stock loading on the dynamic behavior of the soil foundation was investigated using the fourth-order Runge-Kutta method. Horizontal and vertical displacements and accelerations of the soil were obtained at various distances and depths of the foundation model from the railway track axis.

In the second stage, a 3D model of the monolithic frame building was created in the SCAD software complex. Modal analysis of the structure was performed using the subspace iteration method. Two calculation options for the multi-story building were considered.

The first calculation was performed for the action of design load combinations: permanent, sustained, and short-term (snow, wind load). In the second calculation option, the stress-strain state of the building was investigated using the spectral method under the action of design loads and kinematic soil excitation, applied along the height of the building's foundation in the form of acceleration vectors. The accelerations were considered in two directions and added to the design combinations along the two directions of wind load influence.

A comparison of the two calculation options was performed to check the reliability and structural safety of the building.

Keywords: dynamics; finite element method; multi-story frame building; multilayer soil model; modal analysis; forced vibrations.

PROBLEM STATEMENT

Rolling stock serves as a source of ground vibrations that affect buildings adjacent to railway corridors. These vibrations can cause uneven settlement of foundations and additional stress in structural elements of buildings, potentially leading to defects or even structural failures.

For buildings and structures erected in the train traffic zone, there is a need to evaluate the stress-strain state of the structures under the action of ground accelerations caused by rolling stock loading. To obtain reliable results for the analysis of the stress-strain state of structures, it is necessary to select a soil foundation model that closely approximates the real soil environment. In practice, the model of a linearly deformable layer of finite width is the most common, as it only requires specifying the deformation characteristics of the soil - the modulus of deformation E and Poisson's ratio v.

The dynamics of rolling stock are determined by the complex interaction of contact forces, geometric parameters, spring suspension systems, vehicle mass, and damping coefficients [1]. Even when moving on a straight track at low speeds, problems associated with hunting oscillations arise. At higher speeds, significant vertical oscillations and forced lateral oscillations of the wheelset system occur. The dynamic interaction between the train and the railway track changes depending on the nature of the track bed section, wheel and rail irregularities, operating conditions, as well as climatic conditions. Rolling stock loads on railway tracks and the stress-strain state parameters of the track superstructure were in many cases determined using the generally accepted methods of V.V. Bolotin, S.P. Timoshenko, B.G. Korenev, and I.M. Rabinovich.

This work is devoted to the investigation of the influence of rolling stock loads on a high-rise building located in the train traffic zone. A numerical method was developed that allowed determining the foundation soil accelerations caused by the periodic rolling stock load and, considering these accelerations, analyzing the dynamic behavior of a multi-story monolithic frame building located near the train movement.

ANALYSIS OF PREVIOUS RESEARCH

The soil foundation significantly affects the natural frequencies and mode shapes of the building. Ignoring soil properties during the interaction between the foundation and the building can lead to significant errors. This class of problems requires an additional analysis of the soil medium to create correct foundation models and develop effective calculation methods oriented towards the use of powerful computing complexes [2 - 4].

Many publications by domestic and foreign scientists, including [5 – 7], are devoted to the analysis of dynamic loads on buildings, particularly seismic loads, and wave propagation in elastic media. Works [8, 9] are dedicated to recommendations for creating design schemes for building structures.

In studies [10 – 12], the influence on buildings of ground vibrations from the movement of underground trains was investigated. And in a relatively small number of works, methods and models for calculating structures subjected to ground vibrations caused by the movement of surface trains are presented [13 – 16].

In previous publications [17 – 20,25], the authors of this article considered various problems and proposed a methodology for analyzing the influence of ground vibrations on a building using a single-layer soil foundation model. This work demonstrates the calculation results using a multilayer model.

MAIN RESEARCH

In the article, an analysis of the dynamic behavior of a high-rise building under rolling stock loading acting on a multilayer soil foundation was performed. The maximum vertical and horizontal displacements and accelerations of the soil at the boundaries of individual layers of the model were determined. The obtained accelerations were applied to the foundation of the multi-story building. The influence of soil accelerations on the building, located near the train movement, more precisely: at a distance of 60 m, was evaluated.

1. Finite-element modeling of single-layer and multilayer soil foundations

Figure 1 shows the multilayer soil foundation model. The single-layer foundation has already been described in the authors' previous works. The properties of the ballast prism and the parameters of the rolling stock, whose influence on the frame building was investigated in previous publications [17 - 19], are also given there.

The multilayer foundation was modeled in the NASTRAN software complex [20] based on a real geological cross-section that has a depth of 30 m and consists of five soil layers. The physical characteristics of all soils layer by layer are given in Table 1.

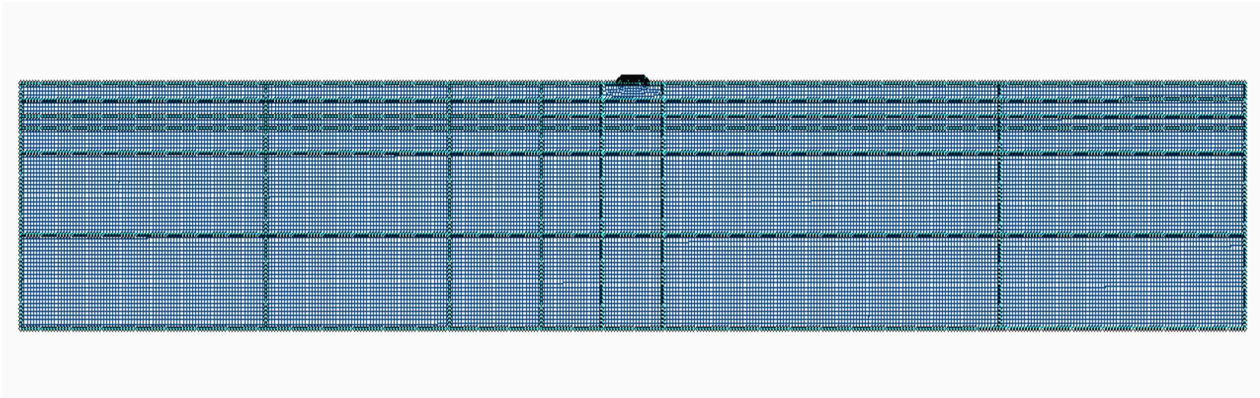

Fig. 1. Finite element model of the multilayer soil foundation
Рис. 1 Скінченно-елементна модель багатошарової ґрунтової основи

Table 1. Physical properties of the soils in the multilayer foundation model
Табл. 1 Фізичні властивості ґрунтів у багатошаровій моделі фундаменту

Layer of soil	Density, g/sm^3	Porosity coefficient	Angle of friction, degrees	Adhesion coefficient, kPa	Modulus of deforma-tion, MPa	Liquidity index	Soil resistivity, kPa
1	1.64	0.61	28.2	0.7	17.3	–	300
2	1.95	0.61	30.9	0.7	28.1	–	200
3	1.82	0.85	14.8	15.3	6.7	0.69	120
4	1.86	0.9	16.5	22.0	12.5	0.34	215
5	1.94	0.9	18.3	28.7	18.5	0.18	220

The rolling stock load is represented as a vertical periodic excitation, concentrated at the center of mass of the system, which consists of the bogie frame, the wheelsets of a freight wagon, and the ballast prism. Fig. 2 shows the horizontal and vertical displace ments of the nodes of the multilayer soil model at different distances from the railway tracks to the building. Figure 3 demonstrates the horizontal and vertical accelerations at distances of 30, 60, and 95 meters.

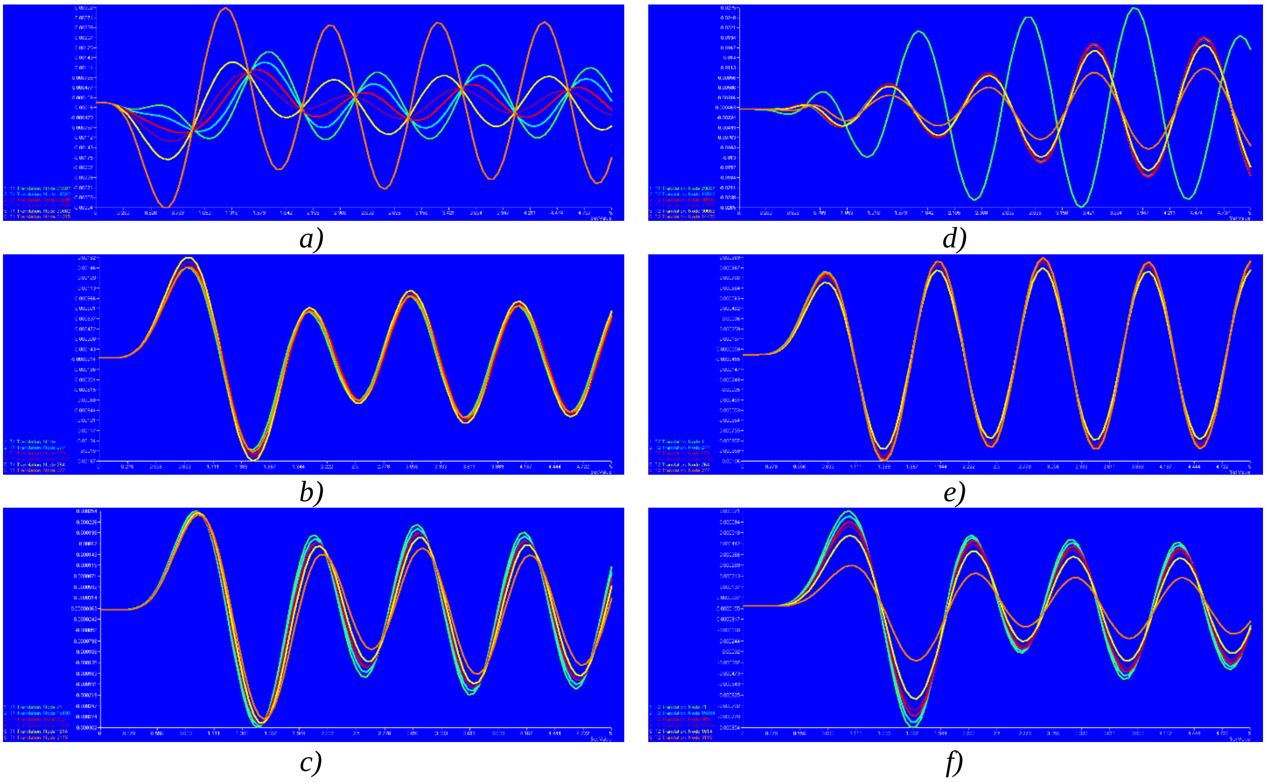

Fig. 2. Displacements of model nodes at distances of 30, 60, and 95 m from the building:
a), b), c) horizontal displacements; *d), e), f)* vertical displacements.

Рис. 2. Переміщення вузлів моделі на відстані 30, 60 і 95 м від будівлі:
а), б), в) горизонтальні переміщення; *г), д), є)* вертикальні переміщення.

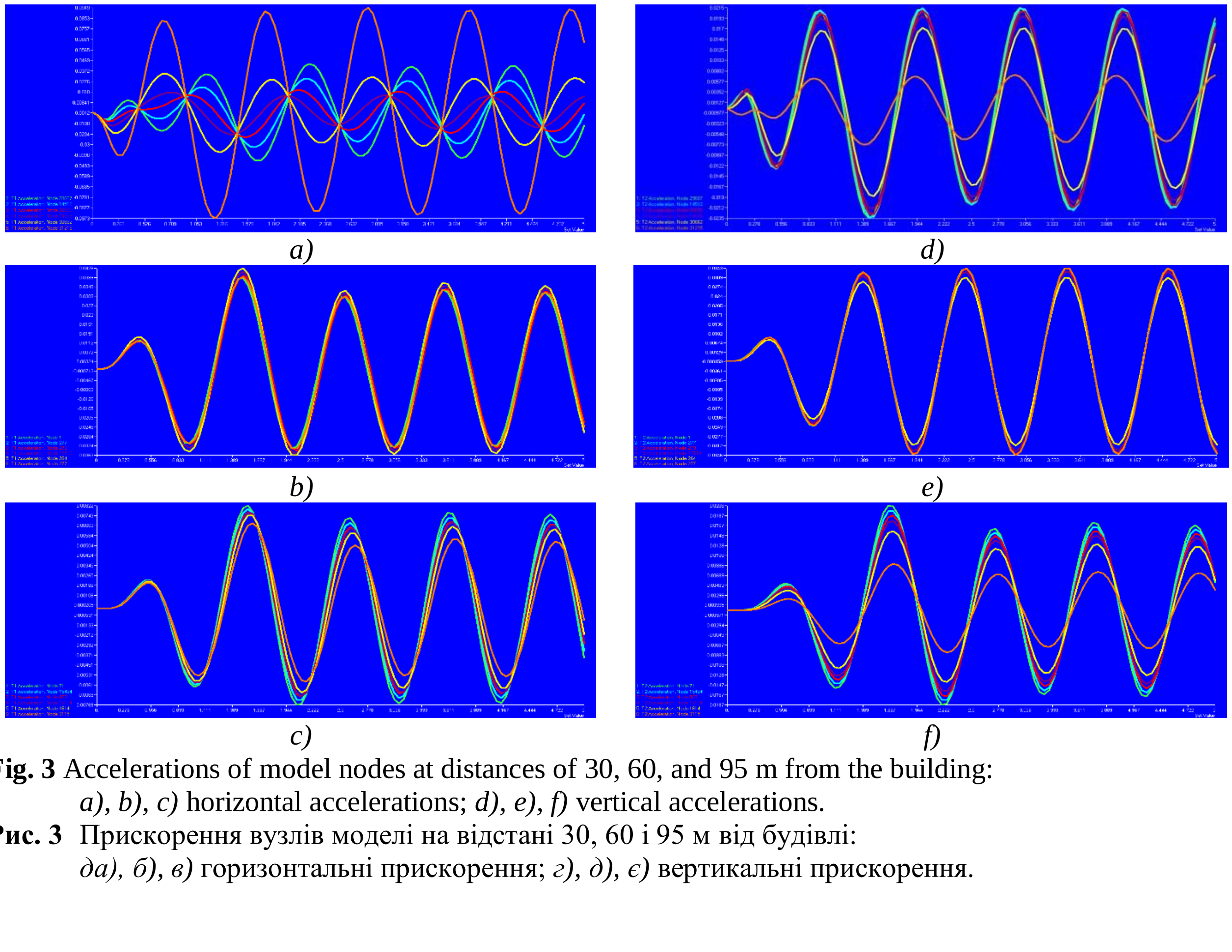

Fig. 3 Accelerations of model nodes at distances of 30, 60, and 95 m from the building:
a), b), c) horizontal accelerations; *d), e), f)* vertical accelerations.

Рис. 3 Прискорення вузлів моделі на відстані 30, 60 і 95 м від будівлі:
да), б), в) горизонтальні прискорення; *г), д), є)* вертикальні прискорення.

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Table 2. Maximum soil characteristics at distances of 30, 60, and 95 m from the building
Табл. 2 Максимальні характеристики ґрунту на відстанях 30, 60 і 95 м від будівлі

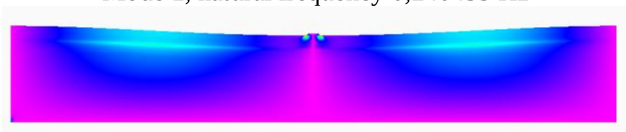
Distance / Depth, m	Total Disp., m	Horiz. Disp., m	Vert. Disp., m	Total Accel., m/s^2	Horiz. Accel., m/s^2	Vert. Accel., m/s^2
30 м / 0 м	-	-	0,0008	-	-	0,0235
30 м / 18,5 м	0,0034	0,0034	-	0,0973	0,0949	-
60 м / 0 м	-	-	0,0011	-	-	0,0346
60 м / 8,5 м	0,0018	0,0016	-	0,0503	0,0428	-
95 м / 0 м	0,0009	0,0003	0,0007	0,0217	0,0082	0,0206

2. Modal analysis of the soil foundation

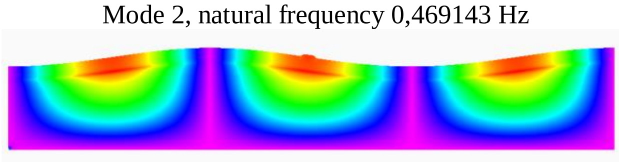
The dynamic calculation of the soil foundation was performed for the action of a vertical periodic load from the movement of a wagon with a load of 230.0 kN; the natural oscillation frequency of the wagon is 6.046 s^{-1}. Modal analysis was carried out using the Lanczos method, retaining 10 mode shapes. In the article [17], the authors described in detail the modal analysis of the single-layer soil foundation model.

This work is devoted to the analysis of the influence of the multilayered nature of the soil. Therefore, modal analysis of the multilayer soil foundation was performed, retaining 10 mode shapes. The mode shapes and natural frequencies of oscillations are presented in Fig. 4.

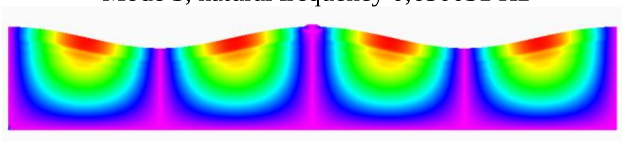
Mode 1, natural frequency 0,240455 Hz



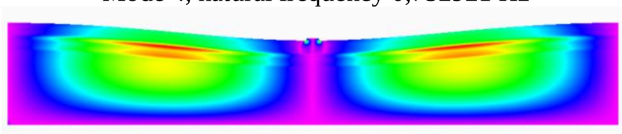
Mode 2, natural frequency 0,469143 Hz



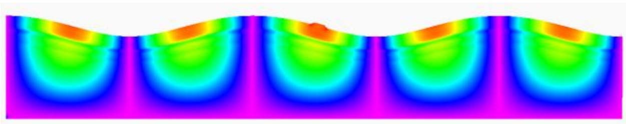
Mode 3, natural frequency 0,650031 Hz



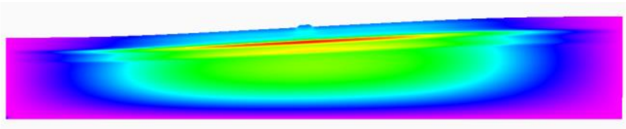
Mode 4, natural frequency 0,752921 Hz



Mode 5, natural frequency 0,832216 Hz

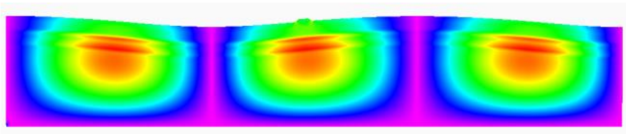


Mode 6, natural frequency 0,83439 Hz

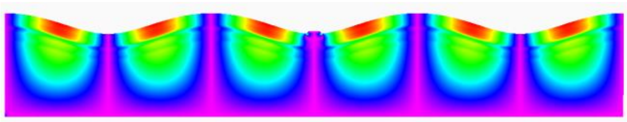


Mode 7, natural frequency 0,847552 Hz

Mode 8, natural frequency 0,888606 Hz



Mode 9, natural frequency 0,897682 Hz



Mode 10, natural frequency 0,922936 Hz

Fig. 4. Mode shapes and natural frequencies of the multilayer soil foundation
Рис. 4. Форми і частоти власних коливань багатошарової ґрунтової основи

For comparison, we present the natural frequencies of the single-layer soil foundation [17]: ν = [0.237372; 0.460532; 0.629739; 0.724444, 0.804174; 0.82192; 0.8382; 0.88234; 0.892783; 0.894094] Hz.

Compared to the single-layer foundation, the natural oscillation frequencies of the multilayer foundation have values 2 - 3% higher, and the mode shapes demonstrate the influence of the multilayered nature.

3. Finite element model of the frame building

A frame multi-story building was investigated, whose finite element model was created using the SCAD office computing complex [21] and is presented in Fig. 5.

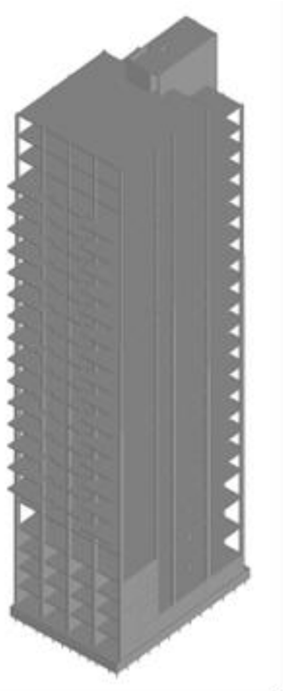


Fig. 5. 3D scheme of the building
Рис. 5. 3D схема будинку

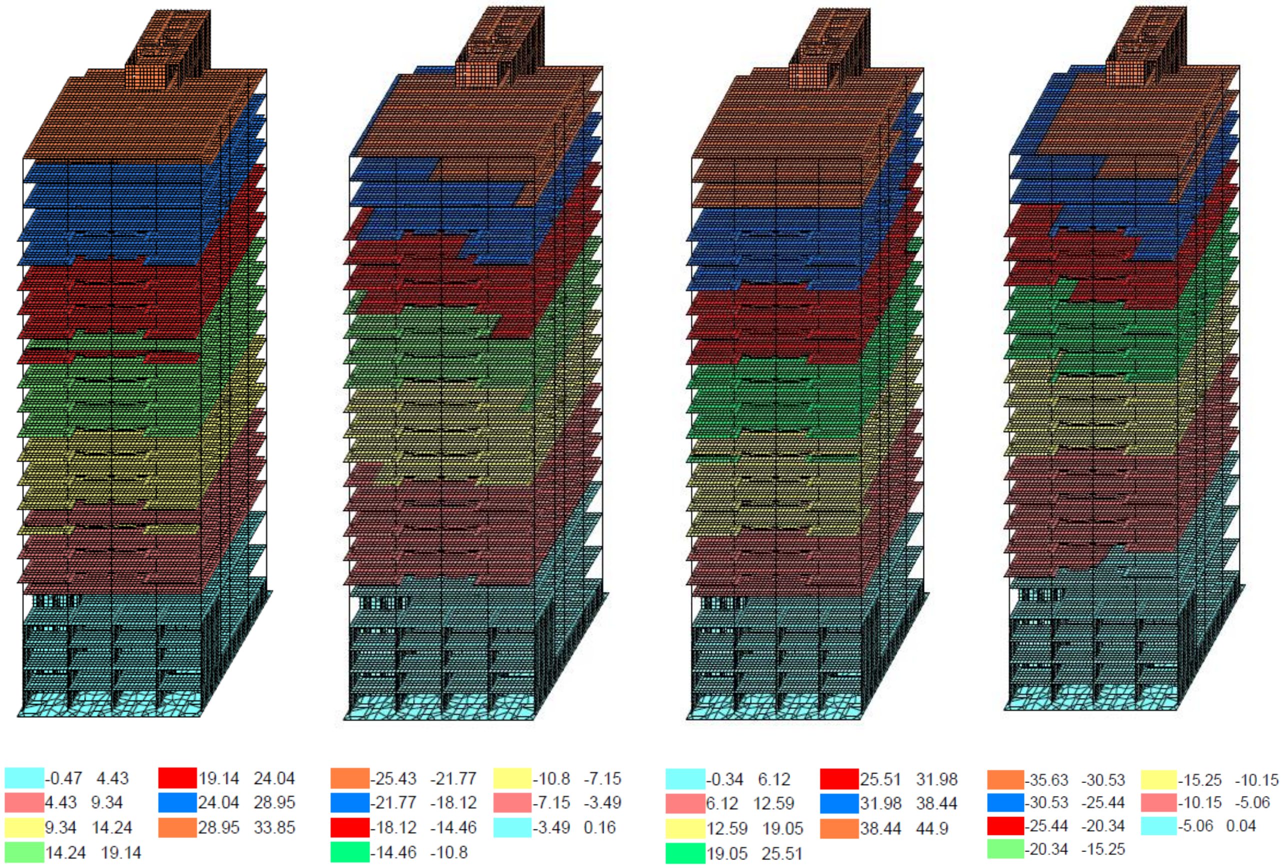
The twenty-three-story building has the following technical characteristics: monolithic reinforced concrete frame, total height 71.9 m, plan dimensions – 24.0 x 21.3 m. A monolithic reinforced concrete raft on a pile foundation with bored piles was adopted as the foundation. The floors and roof are monolithic reinforced concrete flat slabs (beam-free). The wall material is inter-frame infill made of brick and aerated concrete blocks. The height of a typical floor is 3.3 m. The structural system of the building is a moment-resisting frame with bracing (frame-braced system). Two calculation options were considered: the first was performed for the action of design load combinations, and in the second option, the stress-strain state of the building was additionally investigated using the spectral method under kinematic soil excitation, applied along the height of the building's foundation in the form of acceleration vectors. The accelerations were considered in two directions and added to the design combinations along the two directions of wind load influence.

4. Dynamic behavior of the frame building from rolling stock action

The dynamic calculation of the building was performed for the action of soil accelerations, assuming that the rolling stock is located at a distance of 60 m. In this case, 10 mode shapes of the building's natural oscillations were retained. The frequencies and periods of oscillations are summarized in Table 3. Figure 6 shows the total horizontal displacements of the frame in two directions, both without and with consideration of the rolling stock influence.

Table 3. Dynamic characteristics of the building's natural oscillations
Табл. 3 Динамічні характеристики власних коливань будівлі

Форма коливань Mode Shape	Частота коливань Frequency	Період коливань Period
	Гц/Hz	с/s
1	0.2723	3.6724
2	0.3133	3.1920
3	0.6662	1.5010
4	1.3782	0.7256
5	1.9380	0.5160
6	2.2416	0.4461
7	2.2655	0.4414
8	2.5773	0.3888
9	2.6961	0.3709
10	3.0694	0.3258



a) b) c) d)

Fig. 6 Horizontal displacements of the building frame considering rolling stock influence:
a) in the X-axis direction; b) in the Y-axis direction.

Рис. 6 Горизонтальні переміщення каркасу будівлі з урахуванням впливу рухомого складу:
c) у напрямку осі X; d) у напрямку осі Y.

In the direction of the X-axis, the maximum displacement for the combination of permanent, sustained, and short-term loads is 33.85 mm. Upon adding the dynamic load to the combination along this axis, the maximum displacement is 44.9 mm. Similarly, an increase in horizontal displacements is observed in the direction of the Y-axis. The maximum displacement for the first combination is -25.43 mm. For the second combination, the maximum displacement is -35.63 mm.

CONCLUSIONS AND PROSPECTS FOR FURTHER RESEARCH

1. A numerical method has been developed that allows assessing the influence of rolling stock loads on a frame building constructed in the railway track area.
2. Dynamic calculation of the multilayer soil foundation was performed. Horizontal and vertical soil accelerations were obtained at three different distances from the building.
3. The accelerations were applied to the foundation of the multi-story frame building. Two calculation options for the building frame were performed:

static, for the action of design load combinations, and dynamic, for the action of load combinations considering soil accelerations.

4. Comparative analysis demonstrated an increase in total horizontal displacements along the X-axis by 30 percent, and in the Y-axis direction by 40 percent.

At the same time, the total horizontal displacement of the frame does not exceed 0.001, which is within the permissible displacements according to building codes.

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АНАЛІЗ ДИНАМІЧНОЇ ПОВЕДІНКИ КАРКАСНОЇ БУДІВЛІ З УРАХУВАННЯМ БАГАТОШАРОВОСТІ ҐРУНТУ ОСНОВИ

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Анотація. Досліджено вплив навантаження від рухомого складу на двадцятитрьох-поверхову каркасну будівлю, що розташована поблизу руху залізничних потягів у міській забудові. Математичне моделювання динаміч-ної поведінки багатоповерхових будівель при дії навантаження від рухомого складу виконано за допомогою чисельної методики, що складається з двох етапів.

На першому етапі у програмному комплексі NASTRAN сформована скінченно-елементна модель багатошарової ґрунтової основи разом із баластовою призмою у вигляді плоского пружнопластичного напівпростору довжиною 200 м і глибиною 30 м. При цьому використаний реальний геологічний розріз, утворений з п'яти шарів з різними фізичними характеристиками. Навантаження від рухомого складу подано у вигляді вертикального періодичного збурення, зосередженого в центрі мас системи, що складається з рами візка, колісних пар вагону вантажного потягу та баластової призми.

Модальний аналіз ґрунтової основи і баластової призми виконано методом Ланцоша. Досліджено вплив навантаження від рухомого складу на динамічну поведінку ґрунтової основи методом Рунге-Кутти четвертого порядку. Визначені горизонтальні і вертикальні переміщення та прискорення грунту на різних відстаннях і глибинах моделі основи від осі залізничної колії. На другому етапі у програмному комплексі SCAD створена 3D модель монолітної каркасної будівлі. Модальний аналіз споруди виконано методом ітерацій підпросторів. Розглянуто два варіанти розрахунку багатоповерхової будівлі. Перший розрахунок виконаний на дію розрахункових сполучень навантажень: постійних, тривалих, короткочасних (снігове, вітрове навантаження).

У другому варіанті розрахунку за допомогою спектрального методу досліджено напружено-деформований стан будівлі при дії розрахункових навантажень та кінематичного збурення ґрунту, прикладеного по висоті фундаменту будинку у вигляді векторів прискорень. Прискорення враховані у двох напрямках і додані у розрахункові сполучення по двох напрямках вітрового впливу.

Виконано порівняння двох варіантів розрахунку для перевірки надійності і конструктивної безпеки будівлі.

Keywords: динаміка; метод скінченних елементів; багатоповерхова каркасна будівля; багатошарова модель ґрунту; модальний аналіз; змушені коливання.

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