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INVESTIGATION OF THE INFLUENCE OF GROUND ACCELERATIONS IN DIFFERENT DIRECTIONS ON A BUILDING IN THE RAILWAY TRAFFIC ZONE

Olha LUKIANCHENKO[1], Andriy KOZAK[2], Denys KOSTIN[3]

[1,2,3] Kyiv National University of Construction and Architecture
[1]Research institute of structural mechanics
31, Povitrianyh Syl Avenue, Kyiv, Ukraine, 03037

[1]lukianchenko.oo@knuba.edu.ua, https://orcid.org/0000-0003-1794-6030
[2]kozak.aa@knuba.edu.ua, https://orcid.org/0000-0002-3192-1430
[3]kostin.dy@knuba.edu.ua, https://orcid.org/0009-0000-2191-933X

Summary. The article focuses on the impact of loads from railway rolling stock on the condition of the ballast prism, the propagation of vibrations in the foundation, and their effect on the dynamic behavior of a high-rise reinforced concrete frame building. The study examines the dynamic response of a 17-story monolithic reinforced concrete residential building located near railway traffic in an urban environment. The building is elongated in plan and has sections of varying heights, which may influence the stress-strain state of the structural frame under different directions of ground vibrations. Additionally, the effect of ground vibrations on the structural frame depending on the building's orientation relative to railway tracks is analyzed.

To model the dynamic behavior of the high-rise building under the influence of rolling stock loads, a two-stage approach was applied. First, a finite element model of the ballast prism and soil foundation was developed as a two-dimensional elastoplastic half-space with a length of 200 m and a depth of 60 m. The load from the rolling stock was introduced as a vertical periodic disturbance concentrated at the center of mass of the system, consisting of the bogie frame, wheelsets of a freight train car, and the ballast prism.

The influence of rolling stock loads on the foundation was examined using a nonlinear static formulation based on the Newton-Raphson method. Modal analysis of the foundation and ballast prism was performed using the Lanczos method.

Olha LUKIANCHENKO
professor of the department of structural mechanics,
doctor of technical sciences,
professor

Andriy KOZAK
associate professor of the department of structural mechanics, Ph.D., associate professor

Denys KOSTIN
PhD student of the department of structural mechanics

The dynamic behavior of the foundation was analyzed using the fourth-order Runge-Kutta method. Horizontal and vertical ground accelerations were obtained at various distances and depths within the foundation model.

In the second stage, a 3D model of the building was developed. The stress-strain state of the structure was examined using the spectral method under the influence of design loads and kinematic ground disturbances, applied along the height of the building's foundation in the form of acceleration vectors.

The conditions for the reliability and structural safety of the building were evaluated under a combination of loads, including the impact of ground vibrations induced by railway rolling stock. Additionally, the optimal orientation of the building in relation to railway tracks was analyzed.

Keywords: dynamics; finite element method; rolling stock; ground acceleration; high-rise frame building.

PROBLEM STATEMENT

Today, as Ukraine actively collaborates with European Union countries in the transportation sector, an important direction is the deepening of cooperation through the utilization of transit potential. The implementation of infrastructure projects, along with military and technical assistance, raises the issue of an increasing number of railway transport vehicles operating near civilian buildings and structures in densely built urban areas. Therefore, research aimed at determining the impact of ground vibrations caused by rolling stock on buildings located within railway zones is highly relevant.

Developing a mathematical model that enables the study of the effect of rolling stock loads on the dynamic behavior of a high-rise building situated at a considerable distance from the load's source is a complex task. This challenge involves creating a model of a high-rise building while accounting for its interaction with the ground, as well as a model of rolling stock-ground interaction. Since the interaction between rolling stock and railway tracks is a complex problem requiring numerous differential equations, mathematical modeling using computational frameworks is widely applied in vibration studies. To simplify the process, various calculation schemes with different levels of detail are used.

Due to the identical vertical excitations under the left and right wheels of the wheelset, many researchers reduce the rolling stock-ground interaction model to a two-dimensional representation, where the bogie frame and wheelset are assumed to be perfectly rigid bodies with their masses concentrated at their centers of mass. Several approaches exist for incorporating the elastic properties of the ground foundation. The simplest option is the Winkler foundation model, which can be implemented using finite elements with single-point linear elastic springs. However, the primary drawback of this model is its inability to consider the soil's distributed properties. An alternative to the Winkler foundation model is the elastic half-space or elastic layer model, which is the approach adopted in this study.

REVIEW OF PREVIOUS STUDIES

The dynamic effects of moving loads have been extensively studied by researchers. Since 1847, when the Chester Bridge in England collapsed due to the dynamic impact of moving loads, the issue of safe operation of structures under the influence of rolling stock has remained relevant. Early attempts at theoretical solutions to this problem led to the conclusion that dynamic effects are twice as significant as static ones. Since then, theoretical and experimental research has primarily focused on the impact of moving loads on railway tracks and bridges.

The loads exerted by rolling stock on railway tracks and the stress-strain state of track superstructures are often determined using well-established methodologies by V. V. Bolotin, S. P. Timoshenko, B. G. Korenyev, and I. M. Rabinovich.

The stability of train movement was thoroughly studied in the 1930s by G. Marais and remains a relevant topic today. Numerous scientific studies and papers have been dedicated to this issue in recent years. Marais' research is particularly noteworthy as it comprehensively considers all conditions affecting railway rolling stock movement, jointly analyzing the structural quality of both rolling stock and railway tracks. Based on this research, a safety criterion for train motion was established. He was the first to introduce the term "rolling stock stability on railway tracks". This issue is critically important, as modern railways increasingly apply higher axle loads and higher speeds. A significant concern is the risk of resonance phenomena. However, due to internal friction primarily within springs, suspension joints, and support elements vibration absorption is possible, significantly reducing the risk of resonance.

Rolling stock loads on railway tracks consist of vertical and horizontal longitudinal and transverse forces [1]. These forces generate both stationary periodic and stochastic vibrations in structural elements.

Numerous studies have focused on analyzing rolling stock vibrations alongside railway tracks, determining dynamic wheel-to-rail loads, and evaluating equivalent track loading [2]. Other works explore the stress-strain condition, behavior, and degradation mechanisms of ballast prisms [3].

Vibrations caused by high-speed train movement present a serious environmental issue. Many researchers have examined numerical, empirical, and hybrid methods for predicting ground vibrations induced by trains. The theoretical study of vibration propagation generated by harmonic or constant moving loads along a layered beam supported by a layered half-space is discussed in [5]. The soil is modeled as a series of parallel viscoelastic layers resting on either an elastic half-space or a rigid foundation. The railway track, including rails, track plates, sleepers, and ballast, is represented as an infinite layered beam structure.

Several foreign studies [6–14] have investigated the effects of ground vibrations from trains moving through underground tunnels on buildings. Research in [8] has found that piles generally dampen vibration propagation compared to shallow foundations.

The study presented in [15] explores the impact of reinforced subgrades and vibration-protection blocks on ground-transmitted vibrations in surface railway tracks. Reinforcing railway subgrades with higher stiffness materials is commonly applied in soft soil areas to reduce track settlement and deflection while simultaneously mitigating ground-induced vibration transmission.

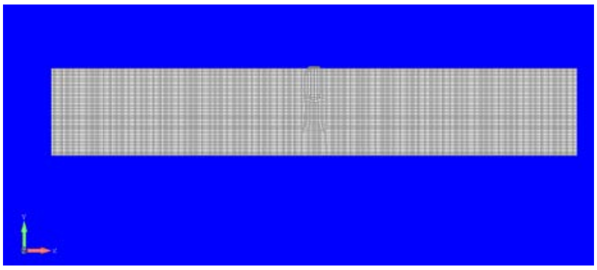
Despite the extensive body of research on various types of structural impacts such as seismic effects and wind-induced pulsations the issue of vibrations generated by above-ground railway transport remains relatively understudied. There is a lack of reliable data on how these vibrations propagate across the earth's surface and affect buildings. Investigating these effects will provide opportunities to ensure safe building operation, prevent structural failure, and protect human lives.

MAIN STUDY

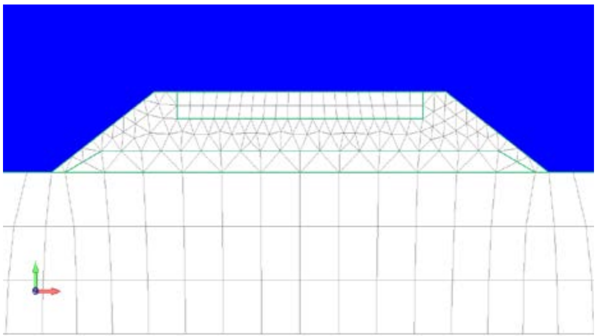
The objective of this research is to examine specific aspects of the impact of train movement and the resulting ground vibrations on a high-rise frame building located near railway tracks.

The characteristics of the foundation and rolling stock are presented in [16]. Soil foundations are considered as a flat elastic half-space.

Figure 1 illustrates the finite element model of the soil foundation along with the ballast prism, developed using the MSC NASTRAN software package [17].



a



b

Fig.1. Computational model of the ballast prism and foundation: a) finite element model (FEM); b) fragment of the FEM

Рис.1. Розрахункова модель баластової призми та основи: а) Скінченноелементна модель (СЕМ); б) Фрагмент СЕМ

The characteristics of the soil were investigated at a distance [0 – 100]m from the action of the

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vertical load in the static and dynamic performances. The nonlinear problem is solved by the Newton-Raphson method of phase-static loading. Dynamic task of determining the eigenfrequencies and mode shapes of the model was performed using Lanczos method. Ground motion together with the ballast under the influence of the vertical load, which is modeled as a periodic load with a frequency equal to the eigenfrequency of the vertical oscillations of the freight a rolling stock were investigated. The task of forced vibration is solved by direct numerical integration of differential motion equations of the Runge Kutta 4th order method.

In the computational model of the building, ground accelerations corresponding to a distance of 50 m were applied at the foundation level. This distance from the railway track axis is the minimum permissible distance for new buildings to mitigate the effects of vibration.

The finite element model of the high-rise reinforced concrete frame building was developed using the SCAD software package [18]. The model comprises 87,148 beam and shell finite elements and 81,478 nodes, each with six degrees of freedom (Fig. 2).

The building has a height of 60.45 m and an elongated plan, with axial dimensions of 50.3 × 22.85 m on one side and 50.3 × 10.65 m on the other. It consists of one underground and sixteen above-ground floors. The first ten floors maintain identical slab contours. Above the 11th-floor slab, the slabs decrease in plan dimensions, forming sections of varying heights. The underground level, which houses a parking area, has a height of 3.6 m, while the first floor, containing commercial and office spaces, has a height of 4.2 m. The typical residential floor height is 3.75 m.

The structural scheme of the building is frame-braced, ensuring adequate rigidity due to a massive core formed by monolithic diaphragms of elevator shafts and stairwells. The infill between the frame elements consists of brick and aerated concrete blocks. The foundation is a monolithic reinforced concrete raft, 1.2 m thick, supported by 171 bored piles.

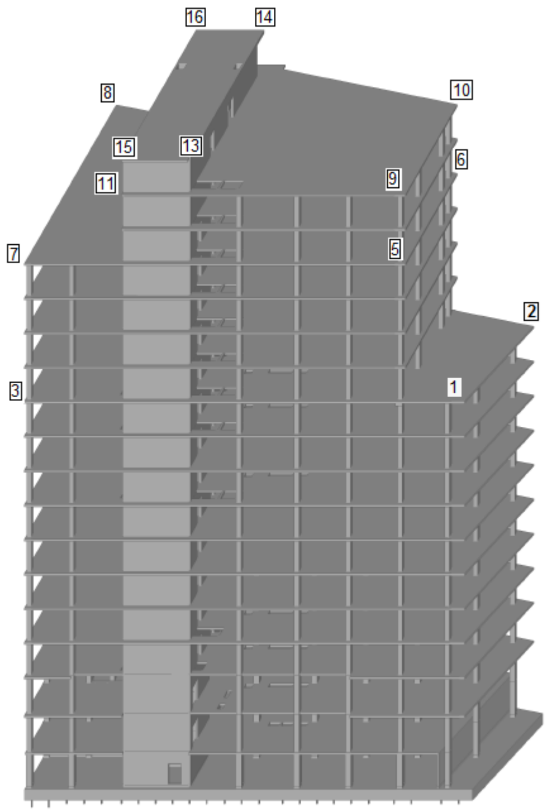


Fig.2. Spatial scheme of the building with numbering of control points

Рис.2. Просторова схема будинку з нумерацією контрольних точок

The dynamic behavior of the building was analyzed under the influence of design static and dynamic loads specified in national regulatory documents [19–20].

Ground vibrations were defined as acceleration vectors applied along the height of the foundation in the computational model.

A modal analysis of the spatial model of the building was performed using the subspace iteration method. Figure 3 presents the 10 eigenmodes obtained from the dynamic calculation.

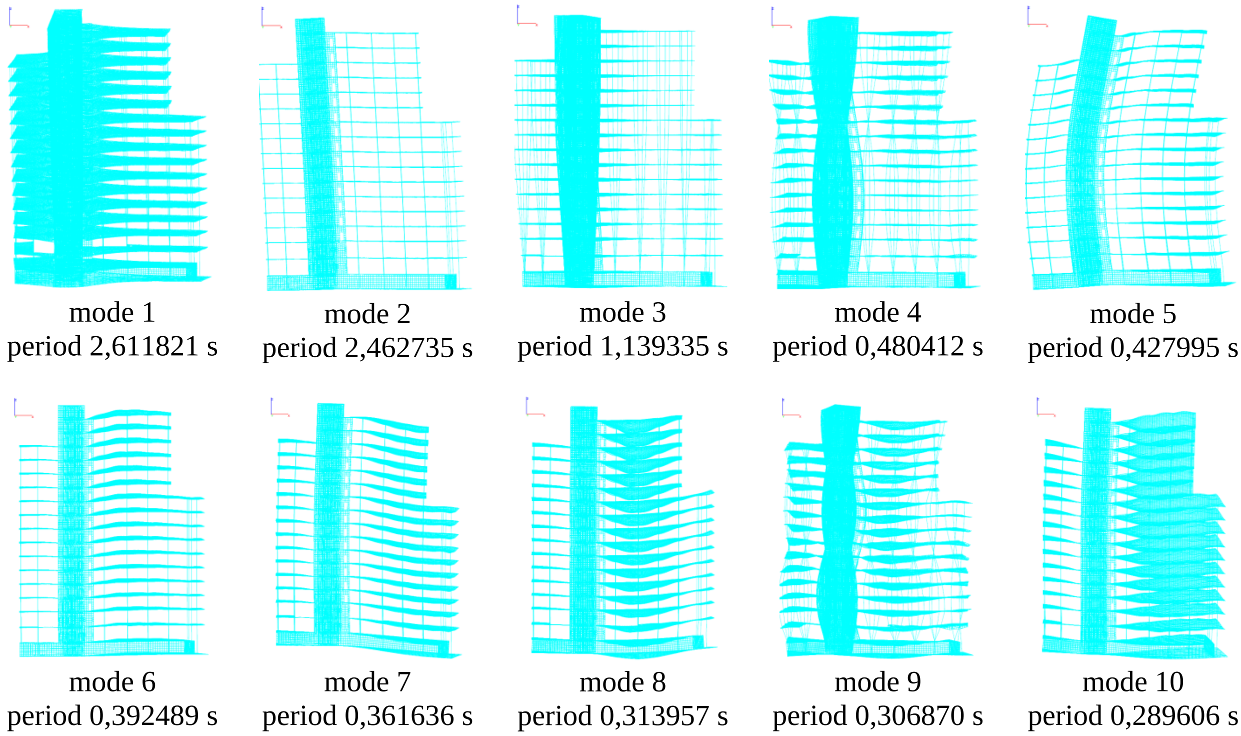


Fig.3. Vertical projections of the building's eigenmodes and corresponding vibration periods
Рис.3. Вертикальні проекції форм власних коливань будинку і періоди коливань відповідно

Two calculation scenarios were conducted: in the first scenario, accelerations were applied in the directions of the global X and Y axes; in the second scenario, accelerations were applied at a 45-degree angle to the X and Y axes.

The horizontal displacements of the building frame were verified (Fig. 4, 5), providing a basis for determining the optimal orientation of the building in relation to railway tracks.

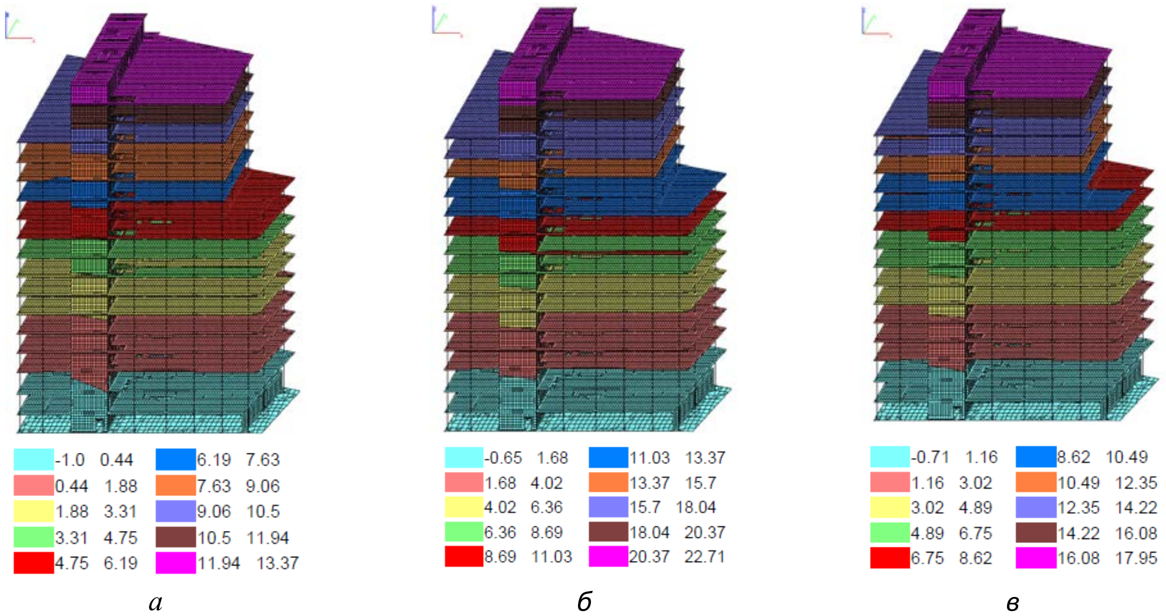
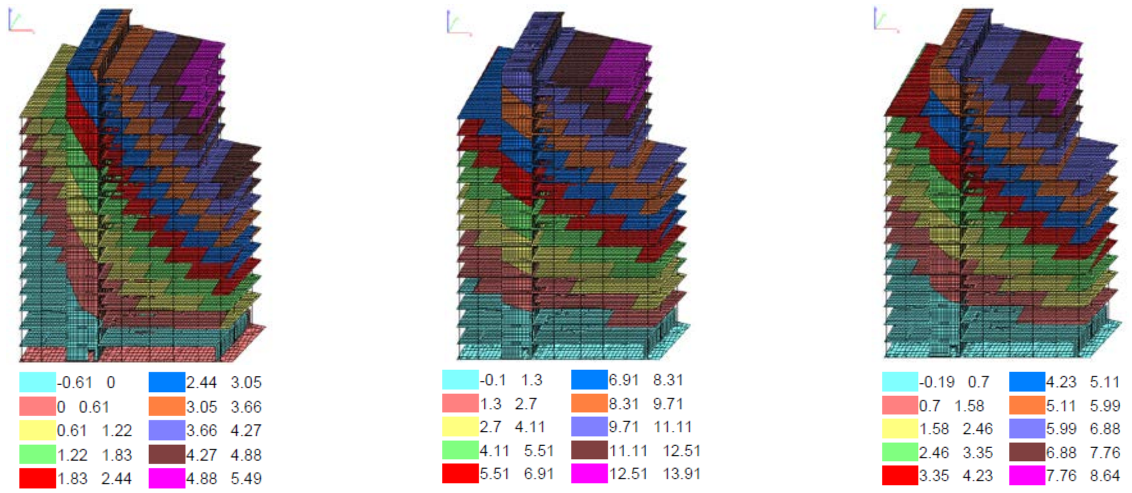


Fig.4. Horizontal displacements of the building frame along the X axis, mm: a) without ground accelerations; b) with accelerations in the X direction; c) with accelerations at an angle to the X direction
Рис.4. Горизонтальні переміщення каркасу по X, мм: a) без прискорень грунту; b) з прискореннями у напрямку у напрямку X; c) з прискореннями під кутом до X



a *b* *c*

Fig.5. Horizontal displacements of the building frame along the Y axis, mm: a) without ground accelerations; b) with accelerations in the Y direction; c) with accelerations at an angle to the Y direction

Рис.5. Горизонтальні переміщення каркасу по Y, мм: a) без прискорень грунту; b) з прискореннями у напрямку у напрямку Y; c) з прискореннями під кутом до Y

Results of the study: horizontal displacements of the building frame, both without and under the influence of accelerations applied in different specified directions at control points marked in the computational model (Fig. 2), are presented in Table 1.

Table 1. Total displacements of the building frame at control points
Табл. 1. Загальні переміщення каркасу у контрольних точках

Point Number	Displacement Along X, mm (No Acceleration)	Displacement Along X, mm (With Acceleration)	Displacement Along X, mm (With Acceleration at an Angle to X)	Displacement Along Y, mm (No Acceleration)	Displacement Along Y, mm (With Acceleration)	Displacement Along Y, mm (With Acceleration at an Angle to Y)
Slab at elevation 30.450						
1	5,70	11,44	8,69	4,65	10,32	6,66
2	5,73	11,25	8,55	4,9	10,64	6,92
3	5,71	11,44	8,69	-0,03	4,48	1,91
4	5,59	10,91	8,27	-0,05	4,46	1,90
Slab at elevation 49.200						
5	9,8	17,68	13,78	5,24	12,71	8,00
6	9,8	17,41	13,57	3,44	12,71	8,00
7	9,76	17,64	13,74	0,76	6,92	3,34
8	9,76	17,16	13,37	0,68	6,86	3,28
Slab at elevation 56.700						
9	11,98	20,91	16,44	5,49	13,91	8,64
10	12,12	20,72	16,32	5,46	13,89	8,62
11	12,1	21,00	16,53	2,27	9,62	5,23
12	12,1	20,64	16,27	2,30	9,64	5,25
Slab at elevation 60.450						
13	13,31	22,71	17,95	3,25	11,26	6,41
14	13,35	22,33	17,67	3,27	11,23	6,43
15	13,30	22,71	17,95	2,47	10,25	5,59
16	13,37	22,35	17,69	2,51	10,29	5,63

As a result of the displacement analysis, it was determined that the orientation of the building at an angle to the railway tracks is more favorable. The impact of kinematic ground excitation applied at an angle to the building was found to be lower compared to the influence of accelerations along the global X and Y axes.

CONCLUSIONS AND FUTURE RESEARCH PROSPECTS

The conducted research has identified a significant impact of ground vibrations induced by rolling stock on a frame building located in the railway traffic zone. The obtained data on the dynamic behavior of the building frame allow us to conclude the following:

- a comparison of displacements without ground accelerations and under their influence revealed a substantial increase in frame displacements at control points.
- displacements along the orthogonal axes of the global coordinate system (X and Y), caused by ground accelerations in these directions, nearly doubled.
- displacements along the X and Y axes due to ground accelerations applied at a 45-degree angle to the axes increased by a factor of 1.5.
- the most favorable building orientation is at an angle to the railway tracks, as this positioning proved to be less vulnerable to the effects of ground vibrations.

Further research may focus on refining the mathematical model of the soil foundation, specifically by incorporating multiple soil layers with varying physical characteristics. Additionally, it would be valuable to examine the behavior of brick and panel buildings within railway traffic zones.

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ДОСЛІДЖЕННЯ ВПЛИВУ ПРИСКОРЕНЬ ГРУНТУ РІЗНИХ НАПРЯМКІВ НА БУДІВЛЮ В ЗОНІ РУХУ ЗАЛІЗНИЧНИХ ПОТЯГІВ

Ольга ЛУК’ЯНЧЕНКО,
Андрій КОЗАК,
Денис КОСТІН

Анотація. У статті приділено увагу впливу навантаження від рухомого складу на стан баластової призми, розповсюд-женню вібрацій в основі та їх впливу на динамічну поведінку багатоповерхової каркасно-монолітної будівлі.

Досліджено динамічну поведінку 17-поверхового монолітно-каркасного житлового будинку, що розташований поблизу руху залізничних потягів у міській забудові. Будівля видовжена у плані, має різноповерхові ділянки, що може вплинути на напружено-деформований стан каркасу при різних напрямках коливань грунту. Також проаналізовано вплив вібрацій грунту на каркас в залежності від орієнтації будинку відносно залізничних колій.

Для моделювання динамічної поведінки багатоповерхової будівлі при дії навантаження від рухомого складу застосовано двоетапний підхід: спочатку сформована скінченно-елементна модель баластової призми і ґрунту у вигляді плоского пружнопластичного напівпростору довжиною 200 м. і глибиною 60 м. 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.

Вплив навантаження від рухомого складу на основу досліджено в нелінійній статичній постановці методом Ньютона-Рафсона. Модальний аналіз основи і баластової призми виконано методом Ланцоша. Динамічна поведінка основи досліджена методом Рунге-Кутти четвертого порядку. Отримані горизонтальні і вертикальні прискорення грунту на різних відстаннях і глибинах моделі основи. На другому етапі сформована 3D модель будинку.

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.

Перевірені умови надійності і конструктивної безпеки будівлі при дії комбінації навантажень, що включає вплив вібрації грунту основи від рухомого складу. А також проаналізовано пріоритетний напрямок орієнтації будівлі стосовно залізничних колій.

Ключові слова: динаміка; метод скінченних елементів; рухомий склад; прискорення грунту; багатоповерховий каркасний будинок.

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