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ANALYSIS OF DYNAMIC BEHAVIOR OF A MULTI-STOREY FRAME BUILDING IN THE RAILWAY TRAFFIC AREA

O.O. Lukianchenko,
Doctor of Technical Sciences

A.A. Kozak,
Candidate of Technical Sciences

D.Ye. Kostin,
Graduate student

Kyiv National University of Construction and Architecture

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The impact of loads from rolling stock on a 25-storey monolithic-frame office building section with a 9-storey parking garage, located near the movement of railway trains in an urban environment, was investigated. A two-stage numerical approach was applied to mathematically model the dynamic behavior of multi-storey buildings under rolling stock loads.

In the first stage, the effect of vibrations from rolling stock on the foundation was studied using computational procedures in the NASTRAN software package. Horizontal and vertical ground accelerations at various distances and depths of the foundation model from the railway track axis were obtained. In the second stage, a 3D model of the building was created in the SCAD software package, and its stress-strain state was analyzed under calculated loads and kinematic ground excitation. The ground excitation was applied along the height of the building's foundation as acceleration vectors.

Keywords: dynamics, finite element method, rolling stock, ground acceleration, multi-story frame building.

Introduction. Enhancing collaboration with the European Union in the transport sector and utilizing Ukraine's transit potential are important directions in joint transport policy. Today, infrastructure projects and initiatives involving technical and military assistance are being implemented. However, the issue of dense urban development remains relevant and requires the attention of specialists from various fields and areas of research. The most pressing issues for metropolises concern the growing number of vehicles and railway traffic near civilian buildings and structures.

A review of the literature revealed that theoretical and experimental studies are primarily focused on the effect of moving loads on railway tracks and bridges. The loads exerted by rolling stock on railway tracks and the parameters of the stress-strain state of the superstructure are often determined using the well-established methodologies of V.V. Bolotin [1], S.P. Timoshenko [2], B.G. Korenev, and I.M. Rabinovich [3, 4]. For instance, in [5], the loads from rolling stock on railway tracks are presented as vertical and horizontal longitudinal and transverse forces. In this context, both stationary periodic and stochastic oscillations in structures under the action of these forces were considered. In [6], the oscillations of rolling stock interacting with tracks were studied. The stress-strain state of structural elements in the superstructure of the track was determined and assessed against strength criteria. The stress-strain state, behavior, and degradation conditions of the ballast prism were examined in [7]. Due to the identical vertical excitations under the left and right wheels of the wheelset, many researchers simplified the model of soil and rolling stock interaction to a plane model. In this case, the bogie frame and wheelset were assumed to be perfectly rigid bodies, with their masses concentrated at the centers of mass. The simplest approach to account for the elastic properties of the soil is the Winkler foundation model. However, its main drawback is the inability to consider the soil's distribution properties. Alternatives to the Winkler model include the elastic half-space model or the elastic layer model.

Despite the extensive number of scientific studies dedicated to investigating various types of dynamic impacts on buildings and structures, the effects of vibrations caused by different modes of transportation remain insufficiently explored. It is well-known that rolling stock generates vibrations in the soil that affect buildings located near railway lines. These vibrations can lead to uneven settlement of foundations and additional stresses in the structural elements of buildings. Currently, there is a lack of reliable data on how vibrations from rolling stock propagate through the soil and impact nearby structures. Of particular importance is the consideration of additional dynamic loads from rolling stock when analyzing the dynamic behavior of multi-storey buildings, which are more sensitive to seismic and wind loads. Ensuring safe operational conditions for multi-storey buildings is essential to prevent their destruction and protect human lives.

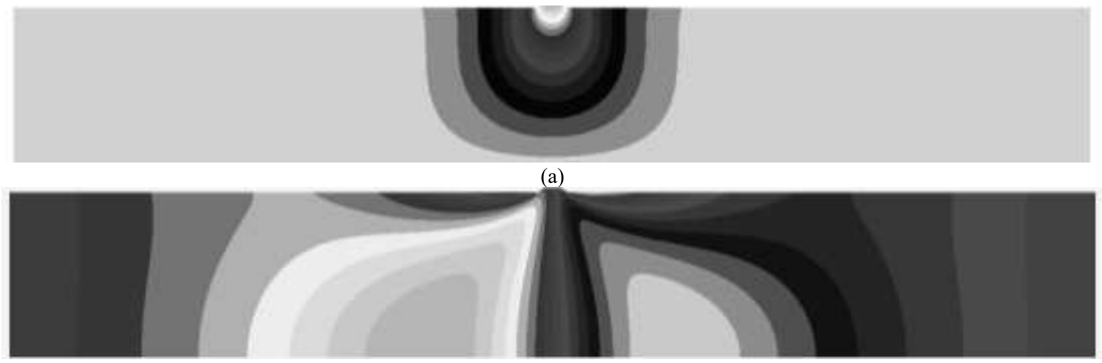
This study focuses on the impact of rolling stock loads on the condition of the ballast prism, the propagation of vibrations in the base, and their influence on the dynamic behavior of a multi-storey monolithic-frame building, taking into account calculated static and dynamic loads as specified by national regulatory documents.

1. Finite Element Model of the Ballast Prism and Base. In the study [8], the authors constructed a finite element model of the ballast prism and the foundation. The soil foundation was treated as a flat elastic half-space. Using elastic-plastic soil properties and corresponding formulas $E_0 = E/(1-\nu^2)$, $\nu_0 = \nu/(1-\nu)$ calculations were conducted for the following physical characteristics of the base and ballast materials: sand (base): $E_0 = 16{,}484\cdot10^3\,\text{kPa}$, $\nu_0 = 0{,}429$, $\beta = 0{,}32$, $\rho = 18{,}0\,\text{kN/m}^3$; sand (ballast): $E = 25\cdot10^3\,\text{kPa}$, $\nu = 0{,}3$, $\beta = 0{,}3$, $\rho = 10{,}0\,\text{kN/m}^3$; macadam (ballast): $E = 5\cdot10^5\,\text{kPa}$, $\nu = 0{,}27$, $\beta = 0{,}27$, $\rho = 14{,}0\,\text{kN/m}^3$; reinforced concrete sleepers: $E = 3{,}8\cdot10^7\,\text{kPa}$, $\nu = 0{,}2$, $\beta = 0{,}05$, $\rho = 24{,}5\,\text{kN/m}^3$.

Rolling Stock Model Specifications (Model 11-260): Purpose: Designed for the transportation of goods, including piece goods and grains, requiring protection.

- Project Number: 260.00.000-00
- Specifications: TU24-5-498-86
- Carrying Capacity: 67 tonnes
- Wagon Tare Weight: 26 tonnes
- Static Axial Load: 228 kN
- Design Speed: 120 km/h
- Base Car Length: 12.240 m
- Overall Length (Coupler Pulling Faces): 16.970 m
- Frame Length (End Girders): 15.750 m
- Maximum Width: 3.266 m
- Maximum Height (Top of Rail Head): 4.688 m
- Height (Floor Level): 1.286 m
- Number of Axles: 4

First, a linear static calculation was performed under a vertical load modeled as a concentrated force of 230.5 kN. This calculation yielded isofields for vertical and horizontal displacements, with a maximum displacement of 0.0536 m (Fig. 1), along with the normal and equivalent stresses for the model.



(a)

(b)

Fig. 1. Isofields of: (a) vertical displacements; (b) horizontal displacements

Next, a modal analysis was conducted to perform a dynamic analysis of the foundation, using the Lanczos method, taking into account the 10 modes and natural vibration frequencies. Figure 2 shows the first 6 natural vibration modes of the foundation. It can be observed that the modes are divided into skew-symmetrical forms (modes 1, 3, and 5) and symmetrical forms (modes 2, 4, and 6).

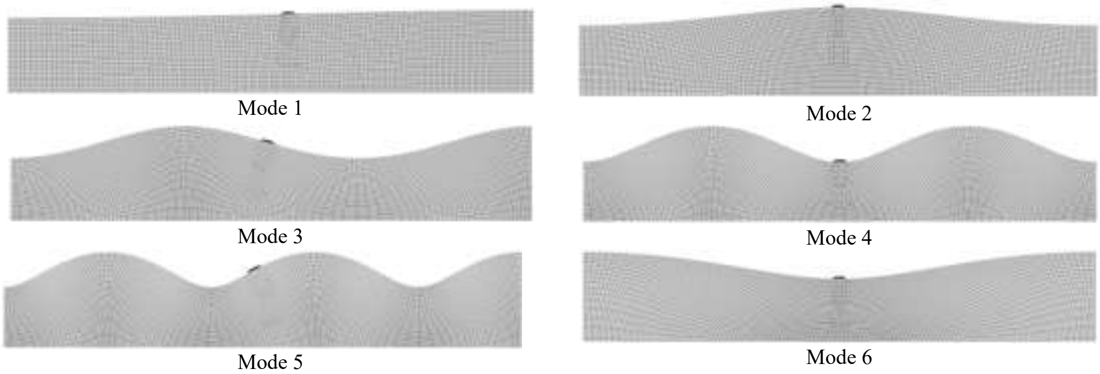
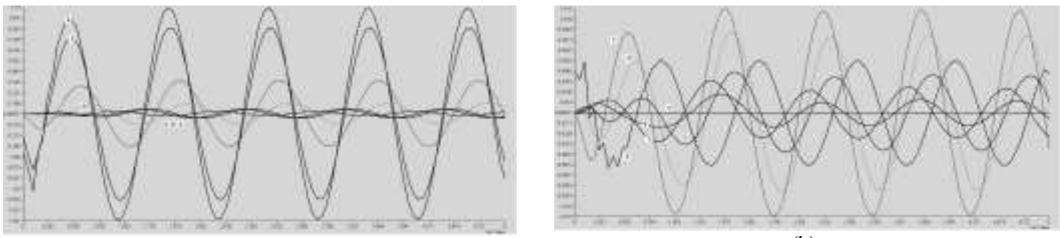


Fig. 2. Forms of natural vibrations
Eigen frequencies constitute: ν = [0,2374; 0,4605; 0,6297; 0,7244; 0,8042; 0,8219] Hz.

The dynamic calculation of the base was performed under the action of a vertical periodic load caused by the movement of the rolling stock, with a load of 228.0 kN. The natural vibration frequency of the rolling stock was determined to be 6,046 s^{-1}. The calculation was conducted through direct numerical integration of the motion equation at the first natural frequency of 0.237372 Hz, with a transition process duration of t = 5 s. This process includes both the inherent harmonic vibration of the model at its first frequency and the influence of the periodic load generated by the carriage with goods. The maximum displacement at the loading point was 0.0357m at t = 0,45s. Consequently, the dynamic response factor is calculated as: 0.0536 m/0.0357 m = 0.67m. If v = 40 km/h the passage time for one rolling stock unit (L = 19.2 m) is t = 1.73s, if v = 100 km/h – t = 0.19 s.

The soil characteristics were studied at distances of [0–100] m from the point of vertical load application under both static and dynamic conditions. The nonlinear problem was solved using the Newton-Raphson method for phase-static loading. The dynamic task of determining the eigenfrequencies and mode shapes of the model was completed using the Lanczos method. The ground motion, along with the ballast, under the influence of vertical loading (modeled as a periodic load with a frequency equal to the eigenfrequency of the vertical oscillations of the rolling stock), was analyzed. The task of forced vibration was solved through direct numerical integration of the differential motion equations using the 4th-order Runge-Kutta method.

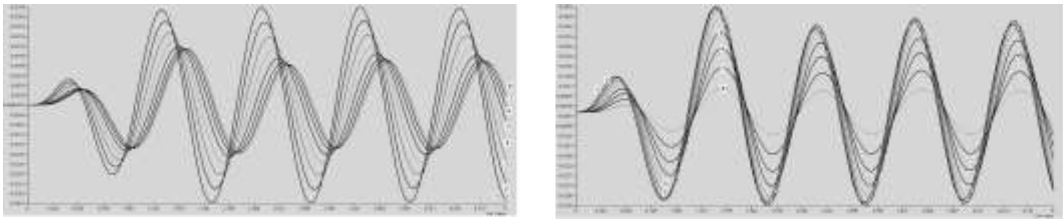
The dynamic behavior of the surface soil layer was examined at distances of [0 – 50] m from the vertical load application (fig. 3). The maximum vertical acceleration of the surface soil layer 1,14 m/s^2, was observed directly at the ballast prism under the loading point. The maximum horizontal acceleration 0.116 m/s^2 was recorded at a distance of 10 m from the loading location. It is evident that vertical ground acceleration decreases with increasing distance from the loading site. However, the horizontal ground acceleration exhibits a non-uniform response to the distance, with values of 0,0256 m/s^2 at 40m and 0,0351 m/s^2 at 50 m.



(a) (b)

Fig. 3. Acceleration of the surface layer of soil
(1 – 0m, 2 – 5m, 3 – 10m, 4 – 20m, 5 – 30m, 6 – 40m, 7 – 50m): (a) vertical; (b) horizontal

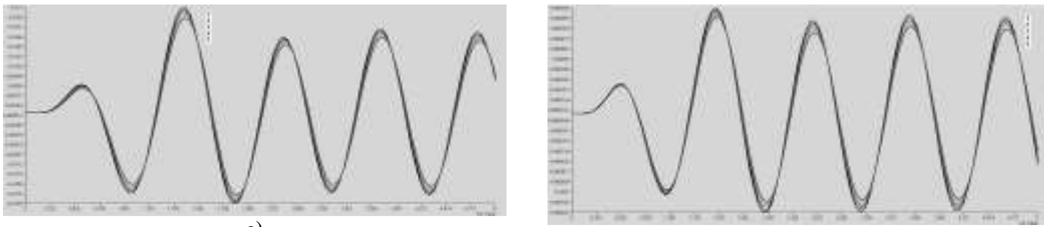
Consider the dynamic behavior of the surface layer of soil at a distance [60 – 100]m from the action of vertical load (fig. 8).



(a) (b)

Fig. 4. Acceleration of the surface layer of soil
(1 – 60m, 2 – 65m, 3 – 70m, 4 – 75m, 5 – 80m, 6 – 85m, 7 – 90m, 8 – 95m): (a) vertical; (b) horizontal

It is observed that, with increasing distance, the vertical and horizontal accelerations of the surface soil layer decrease. The vertical acceleration of the soil ranges from 0.045 m/s² to 0.023 m/s², while the horizontal acceleration ranges from 0.045 m/s² to 0.011 m/s². The influence of the rolling stock on the acceleration of the soil layer at a depth of [0–4] meters and at a distance of 95 meters from the loading point is shown in Fig. 5.

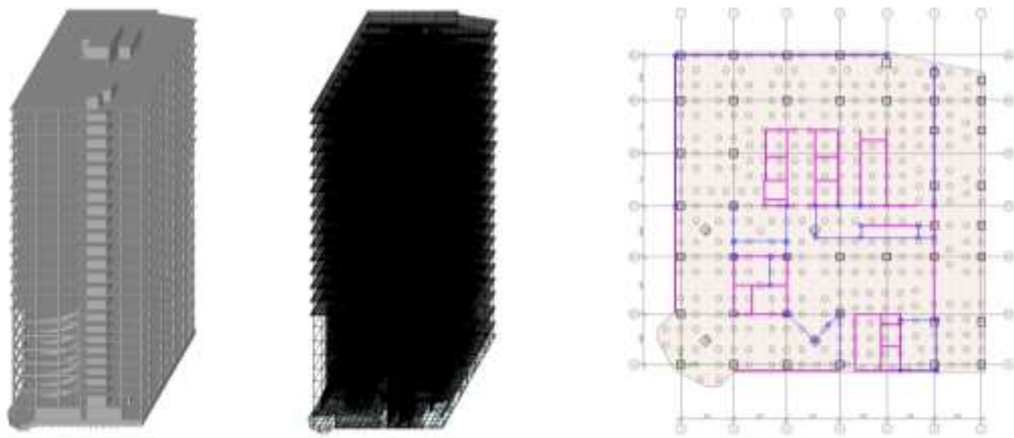


a) b)

Fig. 5. Acceleration in depth soil layer at a distance 95 m
(1 – 0 m, 2 – 1 m, 3 – 2 m, 4 – 3 m, 5 – 4 m): (a) vertical; (b) horizontal

2. **Finite Element Model of a Multi-Storey Building.** The building has a height of 82 meters and dimensions in plan of 35.7 × 36.9 meters. It includes one underground floor and 24 above-ground floors. The first nine floors are partially occupied by a parking garage. The height of each parking level is 3 meters, while the height of the office floors is 3.75 meters. The building exhibits sufficient rigidity due to two stiffness cores, represented by monolithic diaphragms of elevator shafts and stairwells. The inter-frame infill is constructed using bricks and aerated concrete blocks. A monolithic reinforced concrete raft foundation with a pile base consisting of 378 bored injection piles has been adopted as the foundation.

The finite element model of the multi-storey reinforced concrete frame section was developed using the SCAD software package [9]. The model consists of 194,289 beam and shell finite elements and 180,826 nodes, each with six degrees of freedom (Fig. 6).



(a) (b) (c)

Fig. 6. (a) 3D scheme; (b) design scheme in SCAD; (c) basement floor plan, formwork of the monolithic raft foundation and pile field

A numerical dynamic analysis of the building was performed based on the design load combinations in accordance with [10]. In the first scenario, the stress-strain state of the building was investigated under a combination of permanent, long-term, and short-term temporary wind loads, without accounting for ground accelerations at the foundation level caused by rolling stock. In the second scenario, the load combination on the building in two directions of wind load action was supplemented with ground accelerations caused by rolling stock. In the calculation model of the building, ground accelerations observed at a distance of 50 meters from the axis of the railway track were applied at the foundation level.

A modal analysis of the spatial model of the building section was conducted using the subspace iteration method. The dynamic calculation retained 10 natural vibration modes, which are presented in Fig. 7.

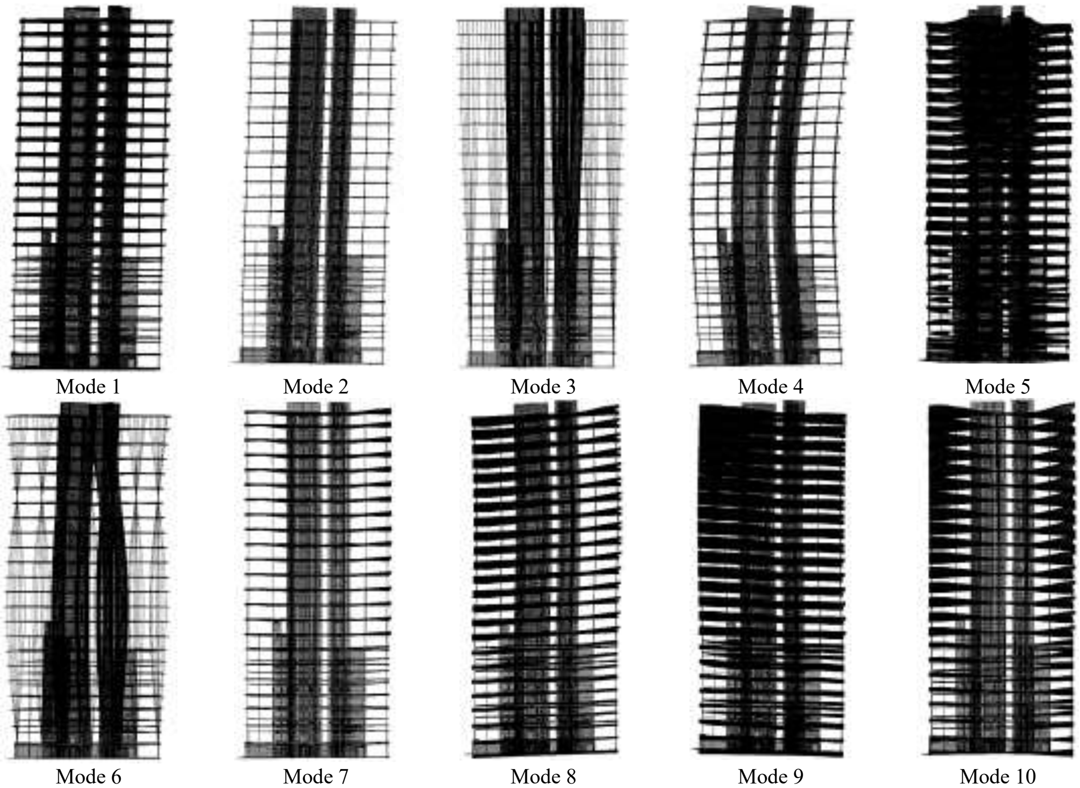


Fig. 7. Vibrational modes of frame

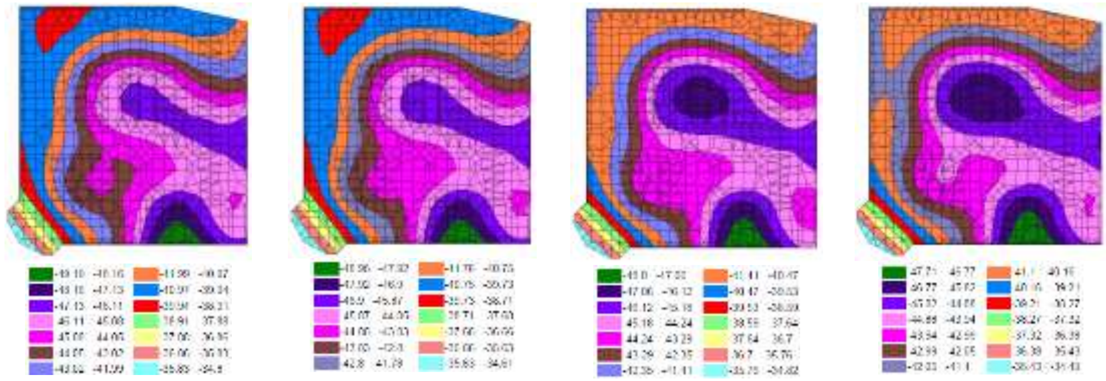
The results of the modal analysis are presented in Table 1.

Table 1

Dynamic characteristics of the building's natural vibrations

Vibration Mode	Vibration Frequency		Vibration Period
	1/s	Hz	s
1	1.845	0.294	3.403
2	1.957	0.312	3.208
3	3.571	0.569	1.759
4	8.773	1.397	0.716
5	9.147	1.456	0.687
6	10.942	1.742	0.574
7	13.706	2.182	0.458
8	15.404	2.453	0.408
9	15.942	2.539	0.394
10	17.338	2.761	0.362

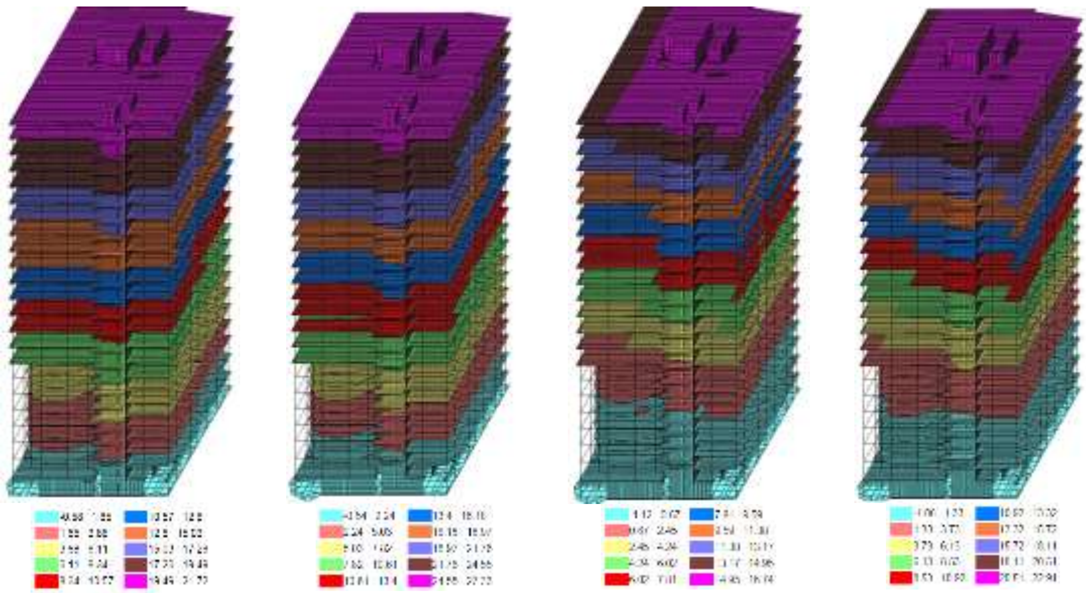
The study revealed that the influence of kinematic ground excitation caused by rolling stock was evident in the changes observed in certain zones of the isofields of vertical displacements of the monolithic foundation raft (Fig. 8). These changes led to a redistribution of loads on the piles and resulted in an increase in the horizontal displacements of the building frame.



(a) (b)

Fig. 8. Vertical displacements of the monolithic raft foundation: (a) Isofields of displacements along *Z*, mm, with and without soil vibrations and under the applied ground accelerations in the *X* direction of wind load; b) Isofields of displacements along *Z*, mm, with and without soil vibrations and under the applied ground accelerations in the *Y* direction of wind load

Fig. 9 presents the isofields of horizontal displacements of the building frame in two directions under the calculated loads, both without and with consideration of kinematic ground excitation caused by rolling stock.



(a) (b)

Fig. 9. Horizontal displacements of the building frame: a) Isofields of displacements along X, mm, with and without soil vibrations and under the applied ground accelerations; b) Isofields of displacements along Y, mm, with and without soil vibrations and under the applied ground accelerations

Conclusion. The proposed numerical approach enabled the investigation of the dynamic impact of rolling stock on vibration propagation in the soil, the determination of ground accelerations at various distances and depths of the foundation, and the analysis of the dynamic behavior of a multi-storey frame building under calculated loads, both with and without the influence of vibrations caused by rolling stock. The study demonstrated that ground vibrations caused by rolling stock are noticeable at the building's foundation level, even at distances permitted by national construction standards. This effect is also evident in the differences in the horizontal displacements of the analyzed building frame, obtained from two dynamic problem scenarios: the total maximum displacement along the X-axis in the first scenario (without ground vibrations) was 27.42 mm, while in the second scenario, it increased to 35.66 mm. This represents a 30% increase in displacement, which is significant. Therefore, to reduce the vibrational impact of rolling stock, new buildings should not be constructed closer than 50 meters from the axis of the railway track.

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Лук'янченко О.О., Козак А.А., Костін Д.Є.

АНАЛІЗ ДИНАМІЧНОЇ ПОВЕДІНКИ БАГАТОПОВЕРХОВОЇ КАРКАСНОЇ БУДІВЛІ В ЗОНІ РУХУ ЗАЛІЗНИЧНОГО ТРАНСПОРТУ

Досліджено вплив навантаження від рухомого складу на 25-поверхову монолітно-каркасну секцію офісного центру з 9-поверховим паркінгом, що розташована поблизу руху залізничних потягів у міській забудові. Застосовано двоетапний чисельний підхід до математичне моделювання динамічної поведінки багатоповерхових будівель при дії навантаження від рухомого складу. На першому етапі сформована скінченноелементна модель баластової призми і ґрунту у вигляді плоского пружнопластичного напівпростору довжиною 200 м і глибиною 60 м в програмному комплексі NASTRAN. Баластова призма і ґрунт представлена сукупністю плоских прямокутних і трикутних елементів із шістьма ступенями вільності у вузлі з відповідними фізико-механічними характеристиками. Максимальний розмір скінченного плоского елемента приймався із урахуванням мінімальної довжини поперечної та повздовжньої хвиль в грунті. На горизонтальні і вертикальні вузлові переміщення лівого та правого країв моделі грунту накладено обмеження, всі вузли нижнього краю моделі грунту жорстко закріплені. Для забезпечення крайових ефектів врахована симетрія моделі ґрунту. Навантаження від рухомого складу подано у вигляді вертикального періодичного збудження, зосередженого в центрі мас системи, що складалася з рами візка, колісних пар вагону вантажного поїзда та баластової призми. Досліджено вплив навантаження від рухомого складу на основу 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 від від осі залізничної колії. На другому етапі в програмному комплексі SCAD сформована 3D модель будівлі, яка представлена сукупністю стержневих і оболонкових скінченних елементів з шістьма ступенями вільності у вузлі. Виконано модальний аналіз будівлі методом ітерацій підпросторів. 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.

Ключові слова: динаміка, метод скінченних елементів, рухомий склад, прискорення грунту, багатоповерхова каркасна будівля.

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Keywords: dynamics, finite element method, rolling stock, ground acceleration, multi-story frame building.

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Досліджено вплив навантаження від рухомого складу на 25-поверхову монолітно-каркасну секцію офісного центру з 9-поверховим паркінгом, що розташована поблизу руху залізничних потягів у міській забудові. Застосовано двоетапний чисельний підхід до математичного моделювання динамічної поведінки багатоповерхових будівель при дії навантаження від рухомого складу. На першому етапі досліджено вплив вібрацій від рухомого складу на основу із застосуванням обчислювальних процедур програмного комплексу NASTRAN. Отримані горизонтальні і вертикальні прискорення грунту на різних відстанях і глибинах моделі основи від осі залізничної колії. На другому етапі в програмному комплексі SCAD сформована 3D модель будівлі та досліджено її напружено-деформований стан при дії розрахункових навантажень та кінематичного збурення ґрунту, прикладеного по висоті фундаменту будинку у вигляді векторів прискорень.

Табл. 1. Іл. 9. Бібліогр. 12 назв.

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The impact of loads from rolling stock on a 25-storey monolithic-frame office building section with a 9-storey parking garage, located near the movement of railway trains in an urban environment, was investigated. A two-stage numerical approach was applied to mathematically model the dynamic behavior of multi-storey buildings under rolling stock loads.

In the first stage, the effect of vibrations from rolling stock on the foundation was studied using computational procedures in the NASTRAN software package. Horizontal and vertical ground accelerations at various distances and depths of the foundation model from the railway track axis were obtained. In the second stage, a 3D model of the building was created in the SCAD software package, and its stress-strain state was analyzed under calculated loads and kinematic ground excitation. The ground excitation was applied along the height of the building's foundation as acceleration vectors.

Tab. 1. Fig. 9. Ref. 12.

Автор (науковий ступінь, вчене звання, посада): доктор технічних наук, професор, провідний науковий співробітник НДІ будівельної механіки, професор кафедри будівельної механіки Київського національного університету будівництва і архітектури, ЛУК'ЯНЧЕНКО Ольга Олексіївна
Адреса робоча: 03037 Україна, м. Київ, проспект Повітряних Сил, 31, КНУБА
Робочий тел.: +38(044) 241-54-20.
E-mail: lukianchenko.oo@knuba.edu.ua, lukianch0907@meta.ua
ORCID ID: https://orcid.org/0000-0003-1794-6030

Автор (науковий ступінь, вчене звання, посада): кандидат технічних наук, доцент, доцент кафедри будівельної механіки Київського національного університету будівництва і архітектури, КОЗАК Андрій Анатолійович.
Адреса робоча: 03037 Україна, м. Київ, проспект Повітряних Сил, 31, КНУБА
Робочий тел.: +38(044) 248-32-37
E-mail: kozak.aa@knuba.edu.ua
ORCID ID: https://orcid.org/0000-0002-3192-1430

Автор (науковий ступінь, вчене звання, посада): аспірант кафедри будівельної механки Київського національного університету будівництва і архітектури, КОСТІН Денис Євгенович.
Адреса робоча: 03037 Україна, м. Київ, проспект Повітряних Сил, 31, КНУБА
Робочий тел.: +38(044) 241-54-20
E-mail: kostin.dy@knuba.edu.ua
ORCID ID: https://orcid.org/0009-0000-2191-933X