

NUMERICAL SIMULATION OF DYNAMIC STRUCTURAL RESPONSE TO VIBRATIONS INDUCED BY RAILWAY TRANSPORT

Alexander M. Belostotsky, Alexander I. Nagibovich, Dmitry S. Dmitriev, Andrey A. Aul, Tatiana N. Vasileva

National Research Moscow State University of Civil Engineering, Moscow, RUSSIA
Research & Development Centre StaDyO, Moscow, RUSSIA

Abstract: This article presents numerical modeling results of prognosed dynamic response for load-bearing structural elements of constructing business complex building to railway transport vibration excitation. The transport vibrations are measured on existing pile foundation heads. The obtained response vibration acceleration evaluated by its spectra in accordance with Russian sanitary normative document.

Keywords: finite element method, vibration excitation, transport vibrations, dynamic analysis, modal analysis, dynamic response, response accelerogram, vibration comfort index

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ДИНАМИЧЕСКОГО ОТКЛИКА НЕСУЩИХ КОНСТРУКЦИЙ ЗДАНИЯ ОТ ВИБРАЦИОННОГО ВОЗДЕЙСТВИЯ РЕЛЬСОВОГО ТРАНСПОРТА

А.М. Белостоцкий, А.И. Нагибович, Д.С. Дмитриев, А.А. Аул, Т.Н. Васильева

Национальный исследовательский Московский государственный строительный университет, г. Москва, РОССИЯ
АО «Научно-исследовательский центр СтаДиО», г. Москва, РОССИЯ

Аннотация: В настоящей статье представлены результаты численного исследования прогнозируемого динамического отклика несущих конструкций строящегося здания Делового комплекса в г. Москва от вибрационного воздействия рельсового транспорта, определённого по результатам натурных измерений на оголовках свайного фундамента, и оценка комфортности пребывания людей в соответствии с российскими нормами.

Ключевые слова: метод конечных элементов, вибрационное воздействие, транспортные вибрации, динамический анализ, модальный анализ, динамический отклик, ответные акселерограммы, комфортность пребывания людей

1. INTRODUCTION

Currently building constructing and designing in railway influence area more often happens in metropolises with highly developed railway infrastructure. Besides this infrastructure extension leads to worsened exploiting building structures vibrational state due to new railway tracks laying closer to existing building and structures. Constructing and existing

buildings and structures turn out to be under the rail transport vibration influence caused by land passenger and freight transportation trains, high-speed trains and underground. There are a few illustrations: residential complex Dominion in Moscow, Russia [1] arranged above shallow subways and the Xi'an Bell Tower in China also arranged above four shallow subways lied in 14 meters from Bell Tower foundation, as well [2].

It is known that the wheel and railway cuts impacts causes the railway transport vibration. Its spectrum and amplitude vary due to different railway construction and vibration waves propagation in the ground and also initial vibration amplitude may increase [3]. Railway transport vibration frequency mostly consists of impact excitation 25-50 Hz components [3]. Transformed transport vibration reaches buildings foundations and according to main vibration excitation frequency leads to various effects on buildings structural elements, such as steel structures fatigue resistance diminution (Bauschinger effect), cracking in concrete and masonry structures (see Fig. 1) [2], finish peeling. Periodic transport vibration leads to worsened well-being of people and equipment malfunctioning.

2. PROBLEM FORMULATION

Evaluation of constructing building load bearing structures dynamic response to vibrations induced by railway transport using numerical modeling approach is processed in 2 stages. The first stage consists of the following steps:

- measuring transport vibration excitation on pile foundation heads with further processing and evaluating;
- selecting smaller excerpt from the whole measured and processed vibration signal for usage as initial data at the next stage.

The second stage consists of the following steps:

- designing the finite element model of load bearing structures of a building;
- processing numerical research of load bearing structures dynamic response in building representative part;
- evaluating obtained in representative parts response structures vibrations according to limit vibration values given in Russian building codes and regulations.



Figure 1. The Xi'an Bell Tower foundation cracking due to periodic forced vibrations caused by underground railway transport

In the current paper the object of study is the constructing business complex building located in Moscow, Kulneva street and Kutuzovsky avenue intersection (see Fig. 2). Subject of research is the people residence vibration comfort for the premises of the object exposed to transport vibration excitation caused by land Moscow underground (Metro) trains and Moscow Central Ring (MCR) trains. Currently under construction building block lettered “B” (further “Block B”) located in railway influence area. The smallest distance between MCR rail tracks and Block B vertical load bearing structures is equal to 22 meters (see Fig. a).

Beside location near railway tracks Block B has following characteristics:

- Block B building is constructed above already existing basement floor structures (5 floors deep). Vertical load bearing structures of Block B placed on existing piles and take only vertical load from existing basement floor slabs (see Fig.3);
- load bearing structures of the Block B are steel frame with steel decking monolithic reinforced concrete floor slabs and reinforced concrete structural cores;
- the maximum span between two load bearing columns rows is equal to 30 meters;
- the complex node connection between fourbranched steel part (above the ground) and reinforced concrete part with circle cross section

(below ground) (see Fig. 4). The underground concrete column part bear to pile grid.



Figure 2. The business complex render: a) an assembly view, b) the Block B render

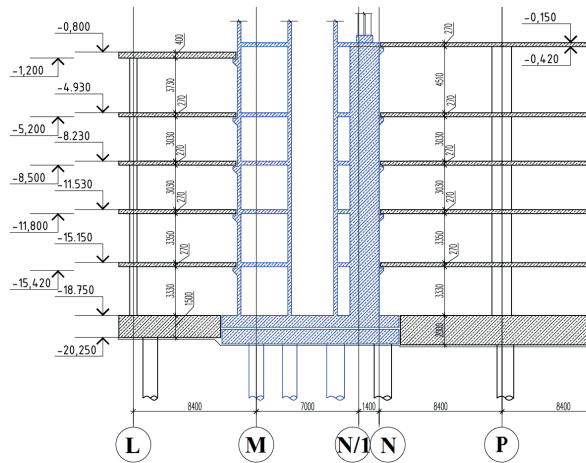


Figure 3. Cross-sectional plan of a five floors basement. New reinforced columns are colored in blue, existing load bearing structures are colored in black

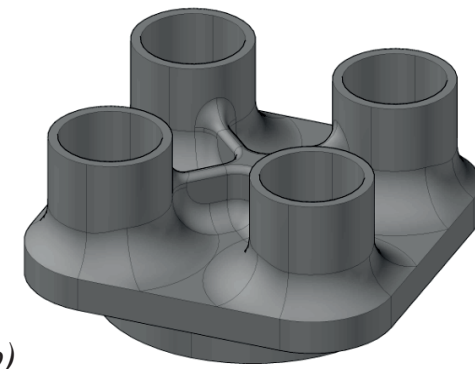
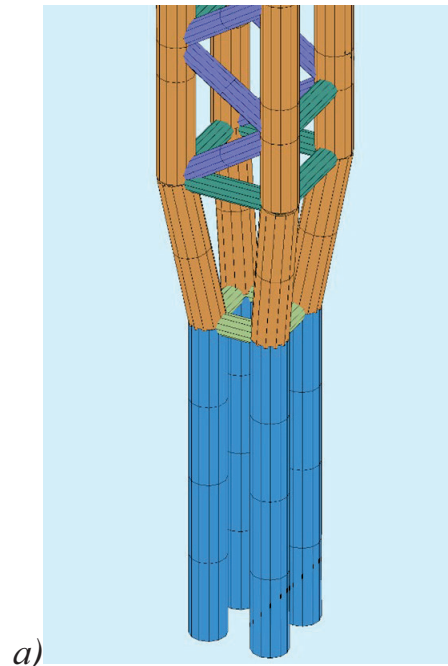
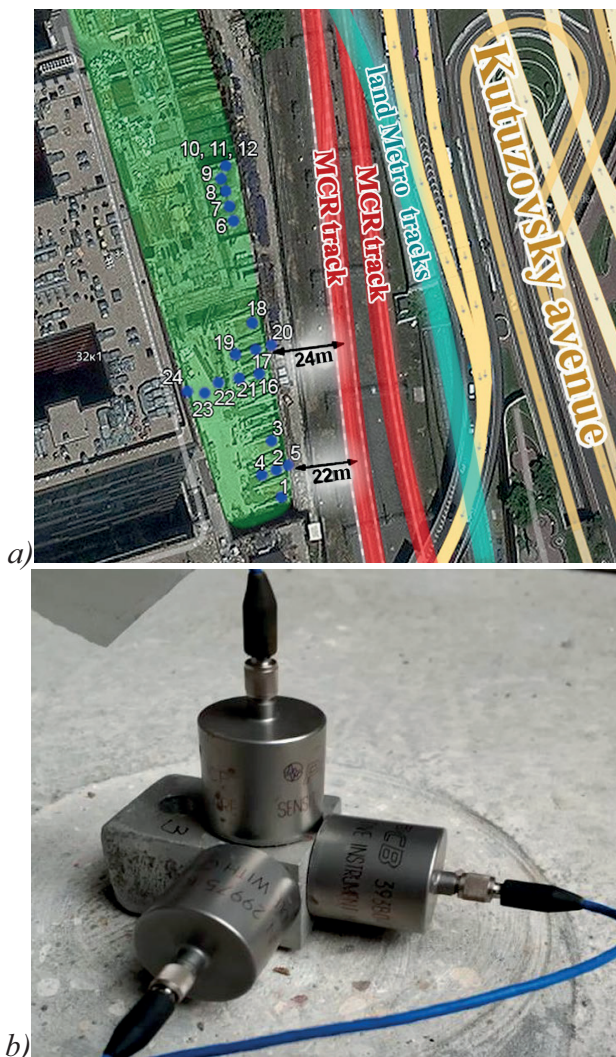


Figure 4. The fourbranched steel bearing column reinforced concrete bearing column node connection: a) an assembly view of column steel part, b) the connection part

3. STAGE 1. MEASURING VIBRATIONS

Taking in account the fact that Block B columns will bear to existing pile grid it was decided to take railway transport vibration measurements on the pile heads (see Fig 4). That provides the lack of need to conduct mathematical modelling of vibration waves propagation in soil mass between Block B pile foundation and railway tracks.

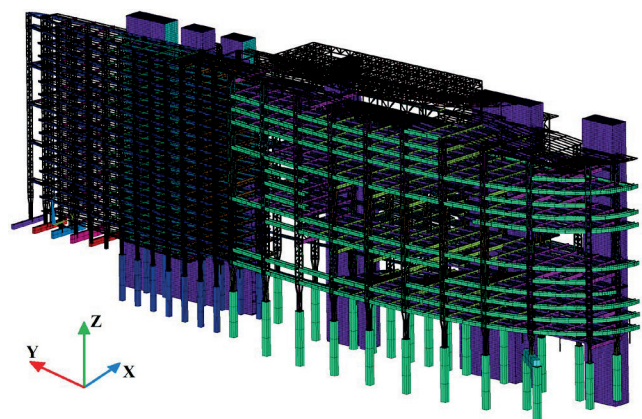


*Figure 5. Vibration measurements.
a) Points of measurements location.*

*Constructing Block B contour is colored green;
b) An accelerometer position on a pile head*

The measurements of railway transport vibration acceleration were conducted by experts Gecha V.Ia., Grabilin A.O., Derishev D.V. from CJSC «Moscow Engineering Agency» taking in account Russian standards [4]. The utilized accelerometers (see Fig. 5b) have from 0.05 up to 750 Hz frequency range and sensitivity in range 100 – 107 mV/ms². The vibration signals measurement and analyzation were made using LMS SCADAS Mobile system. The series of measurement were made. According to the LMS SCADAS Mobile ADC limits and characteristics the sampling rate for each measurement in series was chosen $f_s = 256$

Hz with frequency step $\Delta f = 0,001953$ Hz. Therefore, sampled acceleration signal had $N_s = 131\ 080$ values. According to those characteristics the maximum duration of measured railroad transport vibration signals $T = 256$ s, the discretization step $\Delta t = 2$ ms. The measured in each point (see Fig. 5a) vibration acceleration signals consist of five recorded sequentially signals because the 256 seconds are barely enough to register at least one of Metro or MCR trains passes by nearest railway tracks. Total vibration acceleration signal duration is 1280 s which allowed to measure vibration from at least 5 Metro trains and 3 MCR trains passed in both directions. Railway transport vibration acceleration was measured in 3 directions (see Fig. 6).



*Figure 6. The Block B finite element model.
The direction axes of railway transport vibration excitation are located in the left bottom corner:*

- X and Y direction: horizontal perpendicular and parallel to column rows respectively vibration components;
- Z direction: vertical vibration component

The following measured vibration excitation features were obtained based on its analysis results:

- all measured vibration acceleration signals have low-frequency (significantly lower than 1 Hz) components;
- some of the obtained acceleration signals recorded in few points have an insignificant extraneous noise (lower than 50 dB);

– some of the obtained acceleration signals recorded in a few points have a significant noise from working vibration and impact equipment. Measured railway transport vibration acceleration signals were filtered before further research. Filtration was obtained by extracting components with frequency from 1 to 200 Hz, the components with frequency lower than 1 Hz and higher than 200 Hz were deleted. Besides components of noise with 50 Hz frequency were cut too. Obtained in point 1 at the axis 35 pile head example of railway transport vibration acceleration signal before and after filtration presented on Figure 7.

The moments when MCR and Metro trains passing by Block B are easy to define on processed vibration acceleration signals. The 10 seconds and 50 seconds fragments for MCR and Metro trains with highest acceleration amplitude were chosen from filtered vibration accelerations signals (see Fig. 7, 10 seconds fragments highlighted pink, 50 seconds fragments highlighted yellow). 1/1 octave spectra were obtained for each of these 10 s and 50 s fragments for further railway transport vibration evaluation.

According to [5] the vibration evaluation must be proceeded with vibration logarithmic grade. This method is commonly used for experimental and numerical studies, as example [6]. The limits for our problem are designated for vibration acceleration logarithmic grade value L_a (in dB) for every of 2 – 63 Hz 1/1 octave band of vibration acceleration. The limit values for each 1/1 octave band took from [5] with amendment in «-10 dB» because the transport vibration excitation is inconstant or periodic excitation. The whole signal, 10 s and 50 s MCR and Metro fragments vibration acceleration obtained in point 1 octave spectra comparison with limit logarithmic grade values presented in Tables 1-3. As it shown for representative point 1, measured and filtered railway transport vibration acceleration octave spectra values do not exceed limit logarithmic grade values.

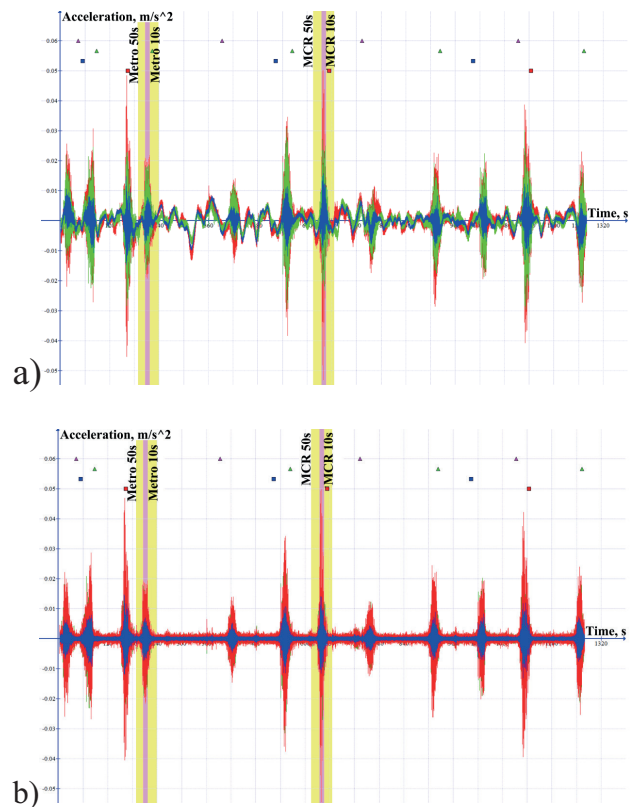


Figure 7. Acceleration history: a) measured; b) filtered. Fragments highlighted pink and yellow were used to obtain vibration signal spectra

Table 1. 1/1 octave spectra for measured in point 1 railway transport vibration acceleration. X direction

Hz	2	4	8	16	31.5	63	125
«Limit», dB	70	71	73	79	85	91	-
1280 s	46	44	45	50	61	63	57
MCR 10s	39	39	47	56	68	71	68
MCR 50s	36	37	45	52	63	66	64
Metro 10s	20	20	25	36	50	52	38
Metro 50s	19	20	23	32	44	46	33

Table 2. 1/1 octave spectra for measured in point 1 railway transport vibration acceleration. Y direction

Hz	2	4	8	16	31.5	63	125
«Limit», dB	70	71	73	79	85	91	-
1280 s	49	47	51	56	63	65	57
MCR 10s	31	46	55	61	72	77	71
MCR 50s	44	45	52	58	66	71	64
Metro 10s	12	11	22	31	42	53	52
Metro 50s	22	25	30	38	47	47	32

Table 3. 1/1 octave spectra for measured in point 1 railway transport vibration acceleration. Z direction

Hz	2	4	8	16	31.5	63	125
«Limit», dB	70	71	73	79	85	91	-
1280 s	34	33	40	45	53	55	49
MCR 10s	44	41	45	50	61	65	60
MCR 50s	38	37	44	47	56	60	55
Metro 10s	11	22	31	42	53	52	38
Metro 50s	15	19	23	32	44	44	33

The 20 seconds fragment with highest amplitude, that cut from measured and filtered railway transport vibration three-component acceleration history obtained in point 1 (630 – 650 seconds), was chosen for the second stage dynamic response research design data. Three components of chosen vibration acceleration fragment illustrated on Figure 8.

4. STAGE 2. STRUCTURAL DYNAMIC RESPONSE NUMERICAL MODELING

The finite element model utilized for Block B dynamic response analysis were designed in ANSYS Mechanical Software. It consists of spatial discretization of Block B above ground structural load bearing elements and below ground new reinforced concrete columns and structural cores). The reinforced concrete and steel columns and beams are modelled with the 3D 2-node beam BEAM188 finite elements (the element is based on Timoshenko beam theory which includes shear-deformation effects), the steel decking monolithic reinforced concrete floor slabs, walls and structural cores are spatially discretized with the elastic shell SHELL63 finite elements (has both bending and membrane capabilities). The FE model consisted of 846 158 nodes and 282 903 finite elements. Every node has 6 degrees of freedom.

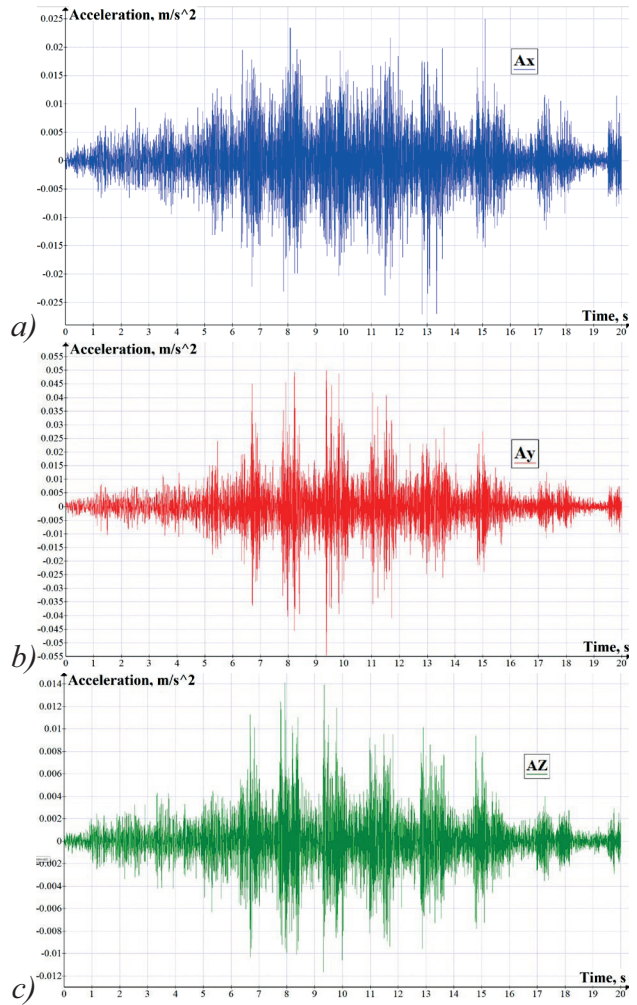


Figure 8. Three components of railway transport vibration acceleration 20 seconds history utilized for the next stage numerical research

Element material properties are presented in Table 4.

Table 4. Material properties

Material	Elastic Modulus E, GPa	Poisson's ratio ν	Density ρ , kg/m ³
Reinforced concrete	36	0.2	2500
Steel	206	0.3	7850

There were designed two options of railway transport vibration excitation (taken as the 20 seconds three-component acceleration history according to stage 1 measurements) distribution scheme to evaluate people residence vibration comfort for the premises of Block B. The first

load distribution scheme (further Option 1) illustrates the platform vibration load distribution, hence vibration acceleration history is simultaneously applied to the all of underground columns lowest nodes right where the reinforced concrete underground load bearing columns bear to the existing piles (see Fig. 9a). And the second load distribution scheme (further Option 2) illustrates the non-platform vibration load distribution, unlike Option 1, the vibration acceleration applies only to the closest to the railway tracks vertical underground load bearing structures lowest nodes (see Fig. 9b). Besides, it's expected that Block B structural elements dynamic response obtained with Option 1 will be higher due to soil railway transport vibration waves damping.

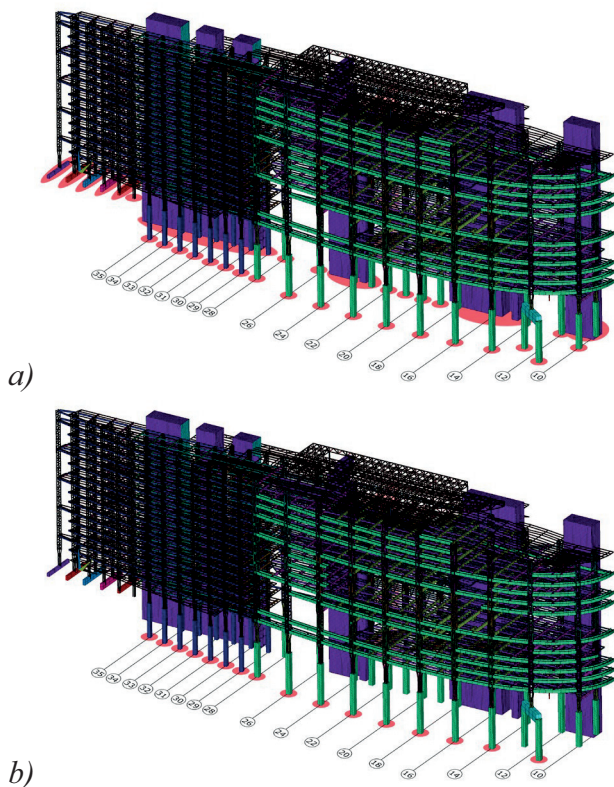


Figure 9. The railway transport vibration load distribution schemes. Nodes to which three-component vibration acceleration history applied to marked with red areas.
 a) Option 1. Platform vibration load distribution scheme;
 b) Option 2. Non-platform vibration load distribution scheme.

The numerical model of the Block B load bearing structures vibration dynamic response problem consists of finite element method semi-discrete equation of motion (see Eq.1). That equation solution can be conducted using direct implicit Newmark method updating equation step by step (see Eq. 2 and 3). The chosen for equations solving time step is equal to 0.002 s. Similar numerical modeling approaches to people residence vibration comfort for the premises of the object exposed to railway transport vibration excitation are presented in articles [1] and [7].

$$[M]\{\ddot{u}(t)\} + [C]\{\dot{u}(t)\} + \left([K] + [K_G]\right)\{u(t)\} = \{F(t)\} + \{R(u, \dot{u})\}, \quad (1)$$

where

$[M]$, $[C]$, $[K]$ и $[K_G]$ – the finite element model structural mass matrix, the structural damping matrix, and the linear (initial) and geometrical stiffness matrixes, respectively;

t – time;

$\{F(t)\}$ – the applied static and dynamic load vector;

$\{R(u, \dot{u})\}$ – the restored load vector utilized for material nonlinear equation solving;

$\{u(t)\}$ – the obtained general nodal displacement vector.

The Newmark time integration method is based on finite difference method. Each Δt time step following velocity and displacement vectors updated as it shown further (see Eq. 2 and 3).

$$\{\dot{u}_{n+1}\} = \{\dot{u}_n\} + \left[(1-\delta) \cdot \{\dot{u}_n\} + \delta \cdot \{\dot{u}_{n+1}\} \right] \cdot \Delta t \quad (2)$$

$$\{u_{n+1}\} = \{u_n\} + \{\dot{u}_n\} \cdot \Delta t + \left[\left(\frac{1}{2} - \alpha \right) \cdot \{\dot{u}_n\} + \alpha \cdot \{\dot{u}_{n+1}\} \right] \cdot \Delta t^2 \quad (3)$$

where

α , δ – Newmark's integration parameters chosen with the accuracy and stability conditions. The optimal parameters ($\delta = 0.5$ and $\alpha = 0.25$) satisfying to both conditions make the Newmark

constant average acceleration method unconditionally stable;

$$\Delta t = t_{n+1} - t_n;$$

$\{u_n\}$ and $\{u_{n+1}\}$ – the vectors of nodal displacements at time t_n and t_{n+1} respectively;

$\{\dot{u}_n\}$ и $\{\dot{u}_{n+1}\}$ – the vectors of nodal velocity at time t_n and t_{n+1} respectively;

$\{\ddot{u}_n\}$ и $\{\ddot{u}_{n+1}\}$ – the vectors of nodal acceleration at time t_n and t_{n+1} respectively.

5. OPTION 1 (PLATFORM SCHEME) RESULTS

The Block B load bearing structures exposed to railway transport vibration specified by three-component vibration acceleration history dynamic response spectra obtained with numerical simulation are compared to limit values represented in [5]. According to this Russian regulation document the determined vibration response acceleration of the structural elements evaluation must be conducted using certain parameter (acceleration) spectral (frequency) analysis. Hence, the logarithmic grade parameter (vibration response acceleration) values must not exceed limit value for each of 1/1 octave bands, given in [5]. The limit logarithmic grade values have been taken with «-10 dB» amendment, due to the transport vibration excitation inconstant nature. Logarithmic acceleration grade values L_a formula is given below (See Eq. 4). The L_a units are decibels (dB).

$$L_a = 20 \lg \frac{a}{1 \cdot 10^{-6}}, \quad (4)$$

where

a – mean average vibration acceleration, m/s^2 ;

$1 \cdot 10^{-6}$ – reference vibration acceleration, m/s^2 .

The steel frame by axis 22 (frame 22) was chosen as representative for numerical modeling results evaluating due to structural core absence

by 22 axis and frame 22 structures span, that is the largest in whole Block B structure. The obtained Option 1 (see Fig. 9a) response vibration acceleration history for representative points in bearing and span areas of frame 22 (see Fig. 10) illustrated in Figure 11. Moreover, the obtained logarithmic grade response vibration acceleration values evaluation for some of these points given in Table 5.

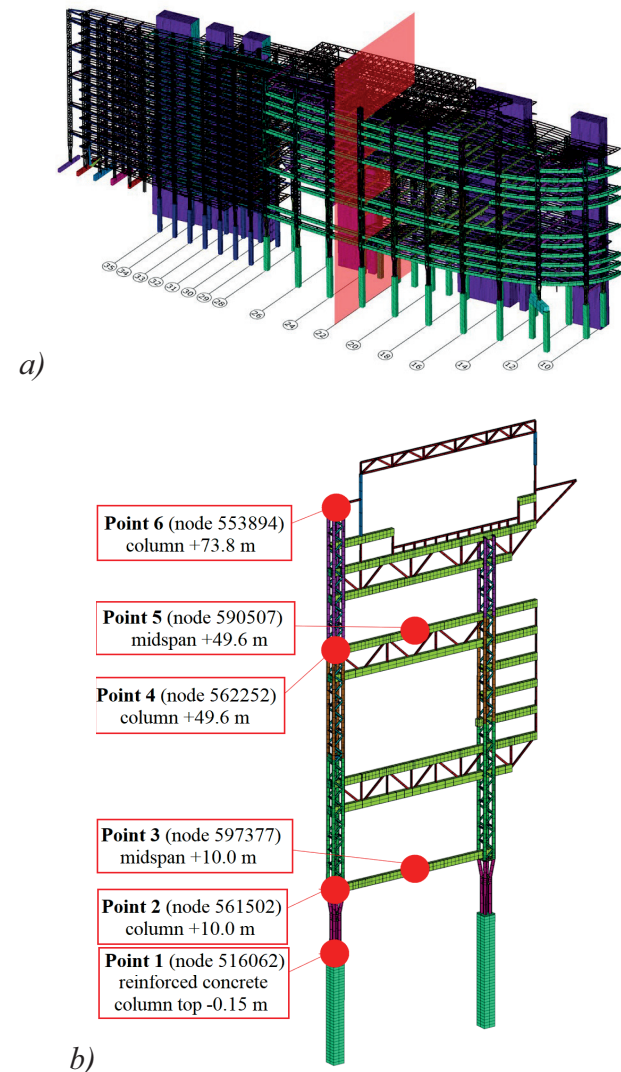


Figure 10. The representative frame by axis 22.

a) Its position in Block B finite element model marked red;

b) The frame 22 structural elements. The representative points in which response vibration acceleration numerical modeling results obtained marked red.

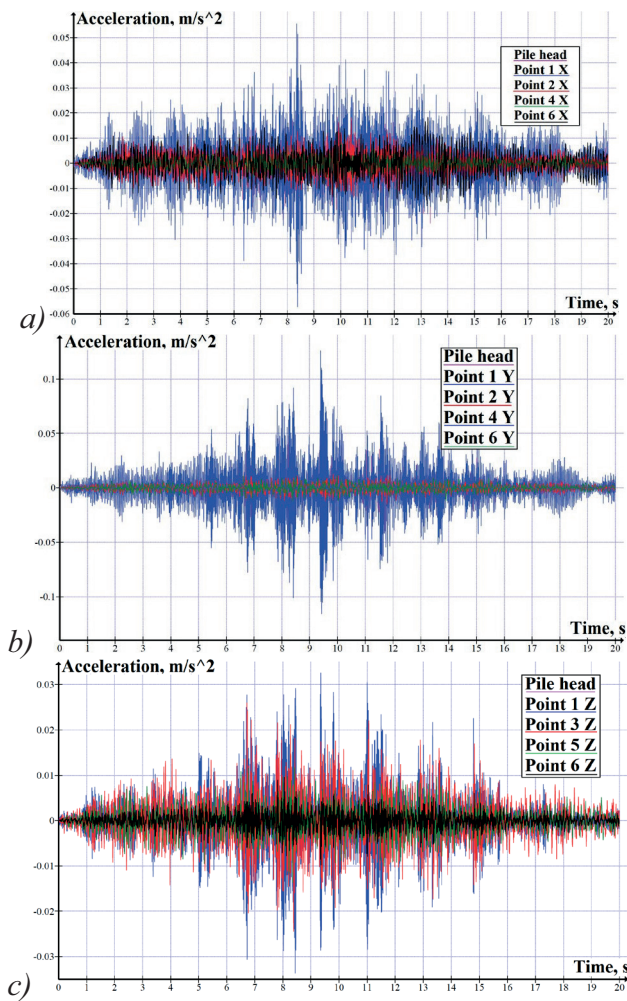


Figure 11. Frame 22 response vibration acceleration history:

- a) A_x , points 1, 2, 4, 6. $A_{x_{max}} = 0.0572 \text{ m/s}^2$
- b) A_y , points 1, 2, 4, 6. $A_{y_{max}} = 0.1255 \text{ m/s}^2$
- c) A_z , points 1, 3, 5, 6. $A_{z_{max}} = 0.0333 \text{ m/s}^2$

Table 5. The logarithmic grade vibration acceleration values at the representative frame 22 points for Option 1 load distribution scheme

Octave band geometric mean frequency, Hz	A_x , point 1, dB	A_y , point 1, dB	A_z , point 1, dB	A_z , point 3, dB	A_z , point 6, dB	Limit, dB
2	40.41	35.79	32.67	35.41	47.53	70
4	59.40	44.05	36.32	60.83	58.32	71
8	51.84	61.90	46.15	68.35	74.48	73
16	75.97	80.52	52.86	68.07	69.85	79
31.5	71.92	74.93	69.67	71.47	68.91	85
63	80.87	86.97	77.06	71.79	59.20	91
125	73.40	70.26	60.98	50.08	29.12	-

*Note: values that exceed residence comfort limits values marked blue.

6. OPTION 2 (NON-PLATFORM SCHEME) RESULTS

The non-platform vibration excitation distribution scheme (Option 2) let us obtain the response vibration acceleration numerical modeling results that are closer to the real structural elements dynamic response due to transport vibration waves dissipation in soil.

The Figure 12 presents the obtained using Option 1 and Option 2 schemes vibration acceleration history comparison for the specific frame 22 representative points in which the residence comfort values those exceed limits were observed. The comparison of logarithmic grade response vibration acceleration values obtained using both platform and non-platform excitation distribution schemes given in Table 6.

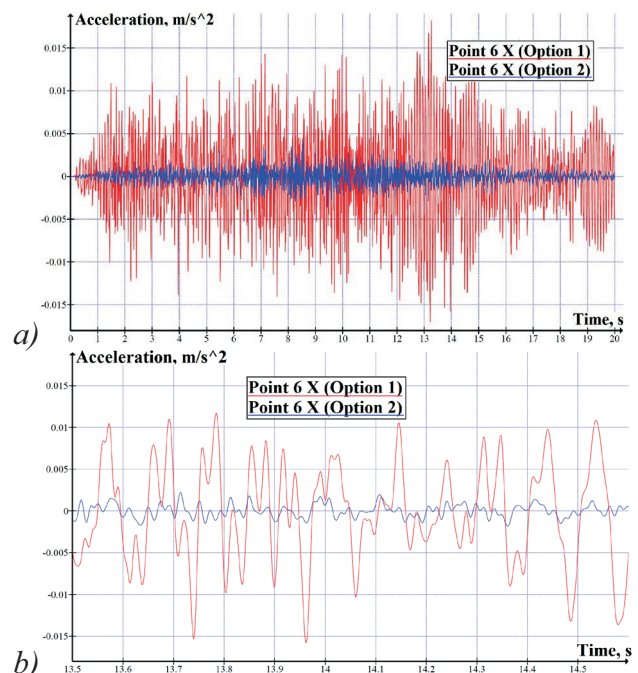


Figure 12. The response vibration acceleration history in X direction at point 6 of frame 22 obtained using Option 1 (platform) and Option 2 (non-platform) schemes.

- a) The whole excitation duration response vibration acceleration history (20 seconds);
- b) The 1.1 seconds fragment (13.5 – 14.6 s) where the vibration acceleration maximum amplitude was observed.

Table 6. The logarithmic grade vibration acceleration values at representative frame 22 6 point comparison for Option 1 and Option 2 load distribution schemes

Octave band geometric mean frequency, Hz	Ax, point 6, dB		Δ , %	Limit, dB
	Option 1 (platform scheme)	Option 2 (non-platform scheme)		
2	47.53	35.25	-25.84	70
4	58.32	52.56	-9.88	71
8	74.48	61.71	-17.15	73
16	69.85	55.81	-20.10	79
31.5	68.91	58.85	-14.60	85
63	59.20	63.53	+7.31	91
125	29.12	20.57	-29.36	-

*Note: values that exceed residence comfort limits values marked blue.

As expected, logarithmic grade values of response vibration acceleration spectra obtained with Option 2 railway transport excitation are within the limit people residence comfort values comparing to Option 1 response spectra exceeding limit logarithmic grade values.

CONCLUSION

Firstly, for the business complex Block B there were measured on existing pile heads and evaluated the vibrations induced by railway transport: land underground trains and MCR trains. Secondly, the Block B dynamic structural response to measured transport vibrations was obtained using finite element model and two vibration excitation distribution schemes: platform and non-platform. The results are described in more details below:

1. The measured on existing pile heads railway transport vibration acceleration octave spectra do not exceed the limit logarithmic grade ones taken according to [5]. For the further object dynamic response numerical research purposes, the 20 second fragment of the three-component acceleration history with maximum measured acceleration amplitude was selected.
2. The two transport distribution schemes were considered: platform (Option 1) and non-

platform (Option 2). The Option 1 railway transport vibration acceleration spectra were obtained for the Block B representative steel frame by axis 22 points located in frame midspans and in load-bearing column areas. The vibration acceleration spectra of point 1 and 6 are exceeding limit logarithmic grade values, hence some of Block B premises are uncomfortable for people residence. However, expected the implausible results for Option 1 scheme.

3. The dynamic response spectra values obtained for Option 2 scheme more likely illustrating the real Block B dynamic response to vibration induced by railway transport are significantly less than limit logarithmic grade vibration acceleration values (reserve more than 10 dB).
4. The comparison of the frame 22 representative points railway vibration acceleration logarithmic grade values obtained for Option 1 and Option 2 schemes shows the expected lower values for Option 2 than Option 1 with 29.36% difference. Except the dynamic response vibration acceleration value for 1/1 octave band with 63 Hz central frequency, for this octave band the Option 2 value higher than Option 1 but yet lower than limit value.

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Alexander M. Belostotsky – DSc, Professor, Full Member of the Russian Academy of Architecture and Construction Sciences, Scientific adviser at Zolotov Research and Educational Center for Computational Modelling of the National Research Moscow State University of Civil Engineering; 129337, Russia, Moscow, Yaroslavskoe shosse, 26. General Director Scientific and Research Center StaDyO; 18, 3ya Ulitsa Yamskogo Polya, Moscow, 125040, E-mail: amb@stadyo.ru

Белостоцкий Александр Михайлович – д.т.н., профессор, академик РААСН, научный руководитель НОЦ КМ им. А.Б. Золотова Национального исследовательского Московского государственного строительного университета; 129337, Россия, г. Москва, Ярославское шоссе, д. 26. E-mail: amb@stadyo.ru

Alexander I. Nagibovich – CSc, Director at Zolotov Research and Educational Center for Computational Modelling of the National Research Moscow State University of Civil Engineering; 129337, Russia, Moscow, Yaroslavskoe shosse, 26. Leading calculation engineer at the Scientific and Research Center StaDyO; 18, The 3rd Yamskogo Polya st., Moscow, 125040, Russia. E-mail: nagibovich@yandex.ru

Dmitry S. Dmitriev - CSc, Senior Research Fellow of A.B. Zolotov REC SM of the National Research Moscow State University of Civil Engineering; 129337, Russia, Moscow, Yaroslavskoe shosse, 26. Deputy General Director for Computational Research of JSC Scientific Research Center StaDyO; 18, 3ya Ulitsa Yamskogo Polya, Moscow, 125040, Russia. E-mail: dmitriev.d.s@yandex.ru

Andrey A. Aul – Head of the sector at Zolotov Research and Educational Center for Computational Modelling of the National Research Moscow State University of Civil Engineering; 129337, Russia, Moscow, Yaroslavskoe shosse, 26. Leading calculation engineer at the Scientific and Research Center StaDyO; 18, The 3rd Yamskogo Polya st., Moscow, 125040, Russia. E-mail: stadyo@stadyo.ru

Tatiana N. Vasileva – engineer at Zolotov Research and Educational Center for Computational Modelling of the National Research Moscow State University of Civil Engineering; 129337, Russia, Moscow, Yaroslavskoe shosse, 26. Calculation engineer at the Scientific and Research Center StaDyO; 18, The 3rd Yamskogo Polya st., Moscow, 125040, Russia. E-mail: rabbitfew@gmail.com

Нагибович Александр Игоревич – к.т.н., директор НОЦ КМ им. А.Б. Золотова Национального исследовательского Московского государственного строительного университета; 129337, Россия, г. Москва, Ярославское шоссе, д. 26. Ведущий инженер-расчетчик АО НИЦ СтаДиО; E-mail: nagibovich@yandex.ru

Дмитриев Дмитрий Сергеевич – к.т.н., старший научный сотрудник НОЦ КМ им. А.Б. Золотова Национального исследовательского Московского государственного строительного университета; 129337, Россия, г. Москва, Ярославское шоссе, д. 26. Заместитель генерального директора по расчетным исследованиям АО НИЦ СтаДиО. E-mail: dmitriev.d.s@yandex.ru

Аул Андрей Андреевич – заведующий сектором НОЦ КМ им. А.Б. Золотова Национального исследовательского Московского государственного строительного университета; 129337, Россия, г. Москва, Ярославское шоссе, д. 26. Ведущий инженер-расчетчик АО НИЦ СтаДиО; E-mail: stadyo@stadyo.ru

Васильева Татьяна Николаевна – инженер НОЦ КМ им. А.Б. Золотова Национального исследовательского Московского государственного строительного университета; 129337, Россия, г. Москва, Ярославское шоссе, д. 26. Инженер-расчетчик АО НИЦ СтаДиО; E-mail: rabbitfew@gmail.com