Ongoing Research in Structural Dynamics at the University of Belgrade

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1 Introduction

The measurements and assessment of road traffic-induced vibrations in 52 buildings along the future light metro (LM) route in Belgrade due to different vibration sources are presented. The numerical model for 2D frame-soil interaction analysis in frequency domain was used to calculate the vibration of two-, six- and twelve-story frame. Frames were modelled by spectral elements, while Integral Transform Method was used to calculate impedance functions of a layered soil. The obtained results are discussed.

2 Road traffic induced vibrations

The measurement of traffic-induced vibrations was carried out on 52 buildings along the future metro line in Belgrade, Fig.2. The scope of investigation was to evaluate the vibration level caused by the existing road and tram traffic, with reference to the potential building damage and the human annoyance, using the existing standards. The investigation work was done for the Belgrade Land Development Public Agency, by the Geological Institute of Serbia, the Geophysical Institute - NIS (Petrol Industry of Serbia) and the Faculty of Civil Engineering University of Belgrade [13]. The designed metro line is about 11 km long (6 km above ground and about 5 km underground) Fig.1. The measurement sites were chosen to represent different types of building structures, importance (historical, institutional, office, and residential buildings) and soil conditions. Before the measurement started the following information on the selected buildings had been collected: geological condition of the site, soil characteristics, building type, building plans and drawings, type of building foundations and floors, distance from the road, etc.

Vibrations in buildings were measured due to the following sources:
1. ambient sources,
2. truck, weighted approximately 14 tons at speed 50 km/h,
3. truck: 14 tons, speed 50 km/h, across rubber ramp 40 cm long and 3 cm high,
4. articulated bus or tram

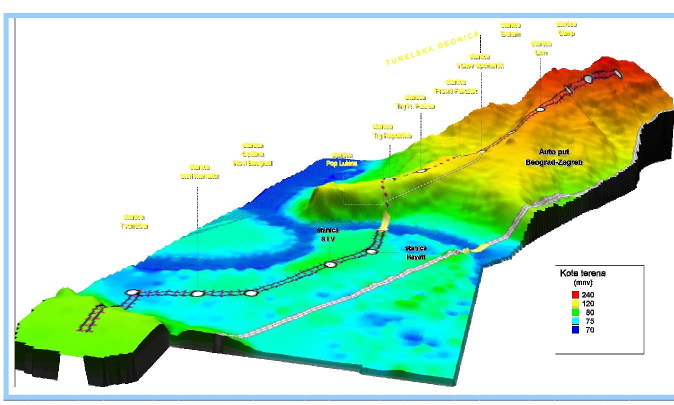


Figure 2.1 3D model of terrain along the LM route

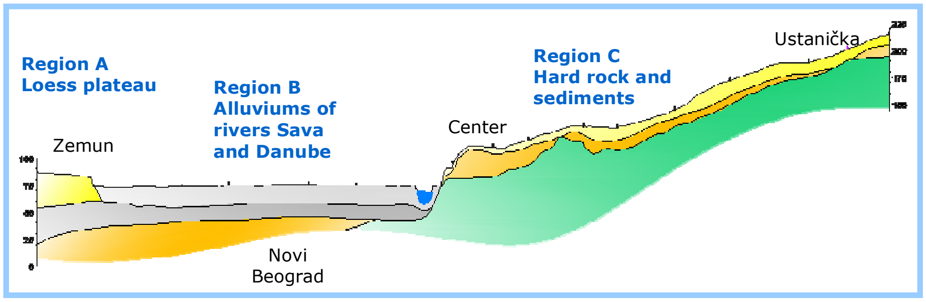


Figure 2.2 Geological profile

2.1 Vibration monitoring

The program of measurement was made by the Faculty of Civil Engineering, University of Belgrade. The measurements were carried out by Geophysical Institute, using I/O System One that consists of 5 three-component geophones, Fig 2.3. The velocities were measured in three orthogonal directions at each point: vertical direction - V, horizontal direction parallel to the road - H1 and horizontal direction perpendicular to the road - H2 [17].

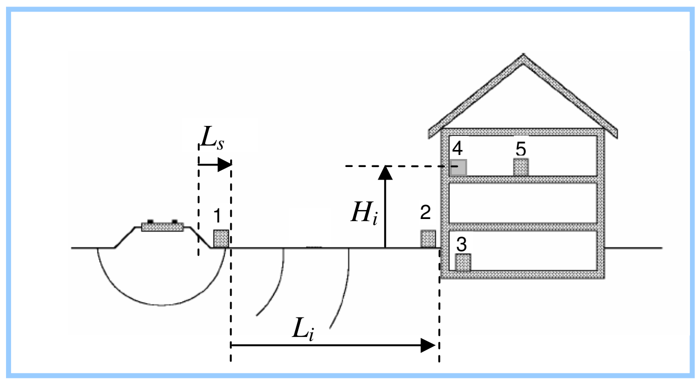


Figure 2.3 Geophone and I-O System One

Figure 2.4 Measurement points

The geophones were positioned at 5 different points at the same location, Fig 2.4, as follows:

- point 1 - on the sidewalk about 1m from the road,
- point 2 – on the ground at the external foundation wall,
- point 3 – in the basement of building close to the external wall,
- point 4 – at the top floor by the wall,
- point 5 – at the top floor at the centre of the room floor.

The control testing was performed to obtain the instrument parameters (resistances of channels, etc). The monitoring of the type and speed of the passing vehicles, traffic frequency and density, time of monitoring, etc. was performed and recorded.

2.2 Results of measurements

During the measurements, a large amount of data was collected and processed. It was found out that the highest vibration levels were measured in the street King's Alexander Boulevard (region C in Fig. 2.2). Generally, higher vibration levels were obtained for vertical vibrations than for horizontal. Therefore, only vertical vibrations of 24 buildings along the Boulevard are presented. Typical time histories and power spectra for horizontal and vertical tram induced ground vibrations at point 2 are plotted in Figs 2.5a - 2.6b.

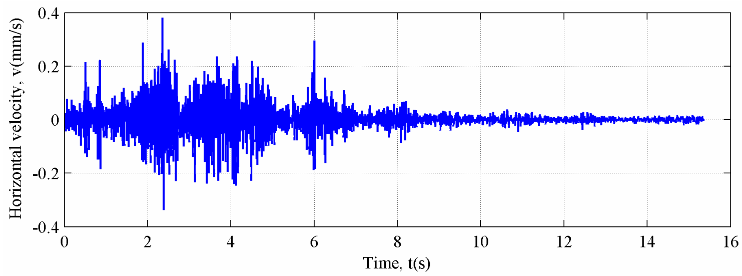


Figure 2.5a Time history of horizontal ground velocity (tram, v=20 km/h, distance to the track 11m)

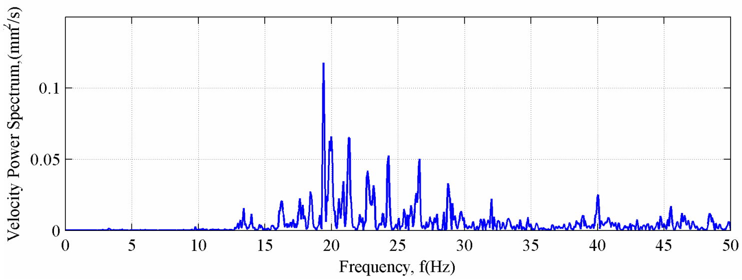


Figure 2.5b Power spectrum of horizontal ground velocity (tram, v=20 km/h, distance to the track 11m)

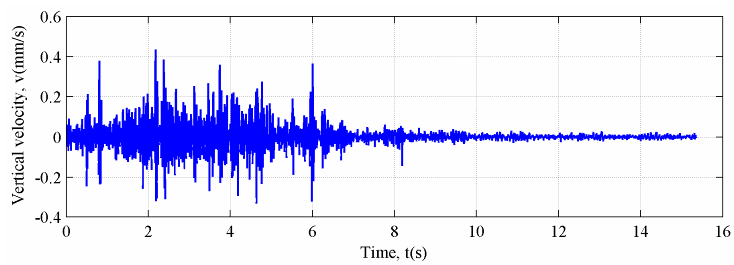


Figure 2.6a Time history and Power spectrum of vertical ground velocity (tram, v=20 km/h, distance to the track 11 m)

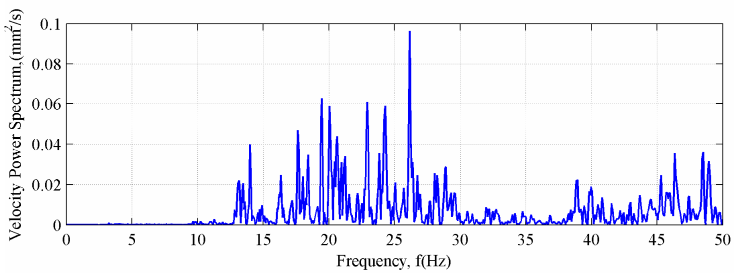


Figure 2.6b Power spectrum of vertical ground velocity (tram, v=20 km/h, distance to the track 11 m)

Fig. 2.7 shows the peak particle velocities (PPVs) in vertical direction, measured at points 1-5, in the buildings 1-24 due to the vibrations induced by tram, truck across ramp and truck, respectively. For truck across the ramp and truck induced vibrations the PPV at the ground nearby the source (point 1) is higher if the site is nearer to the centre of the city. This is not so evident in the case of tram induced vibrations. The reason is evidently the depth of sediment layer above the bedrock. The PPV in point 2 is less than PPV in point 1 at all measurement sites. The reduction of PPVs between point 2 and point 1 in the soil is in the range from 25% for low-rise buildings to 50% for mid-rise buildings. The ratio is relatively high although the distances between two points are relatively short (around 10 m).

In order to assess the influence of building characteristics on traffic-induced vibrations the amplifications of vertical vibrations in the buildings (PPV5/PPV3) were calculated for different class of buildings:

- low-rise buildings are buildings between 1-3 floors,
- mid-rise buildings are buildings between 4-7 floors,
- high-rise buildings are buildings higher than 8 floors.

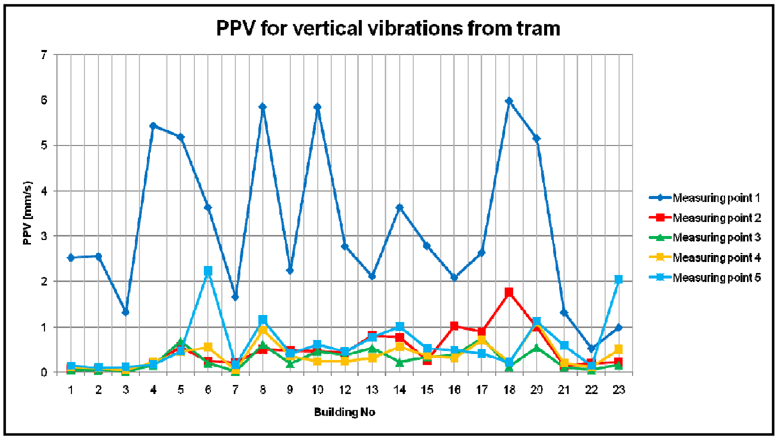


Figure 2.7a PPV velocities in vertical direction due to tram

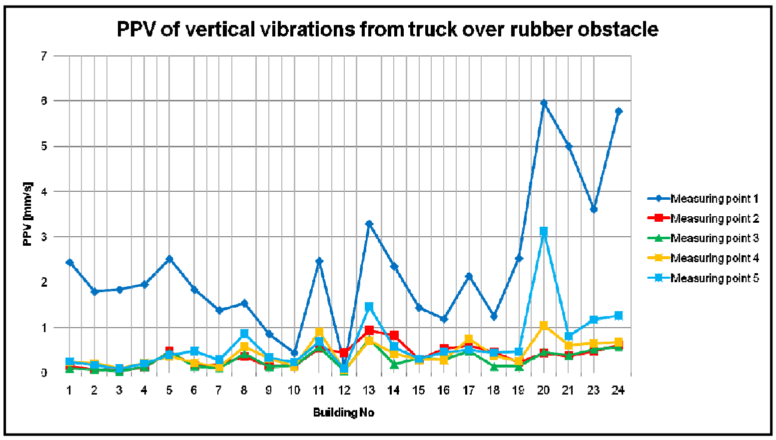


Figure 2.7b PPV velocities in vertical direction due to track over ramp

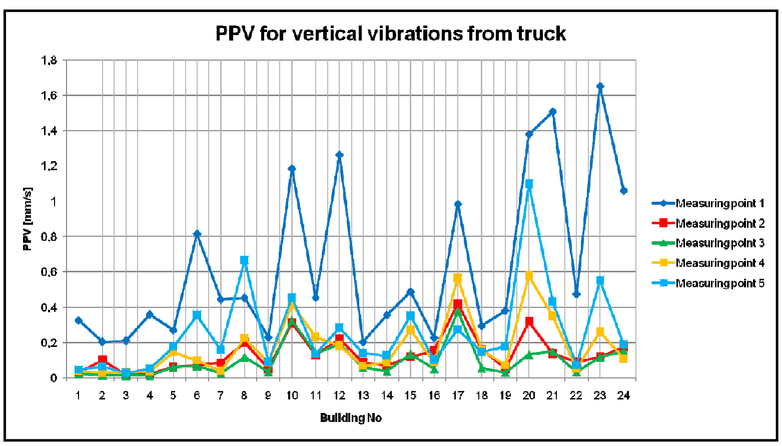


Figure 2.7c PPV velocities in vertical direction due to track

While the mid-rise and the high-rise buildings amplification factors show some regularities, the building amplification factors for the low-rise buildings show considerable discrepancy. The reasons might be the fact that all low-rise buildings, and some mid-rise buildings, in this area are the old type buildings. These buildings have poor, shallow foundations and wooden floors, often weakly linked with the building walls, causing strong vibrations at the middle of the room ceilings in vertical direction and because of that higher amplification factors in the buildings.

The mean values of building amplification factors, given in Table 2.1, show the highest values for the low-rise buildings due to all types of vehicles. The above generalizations may only be used for rough prediction of PPVs inside a building from the PPV measured on the basement. For more accurate estimates of vibration levels at a particular site, it is recommended to use the transfer functions.

Table 2. 1: Mean value of the building amplification factors

Mean values of building amplification factors - PPV5/PPV3			
	low-rise buildings	mid-rise buildings	high-rise buildings
Tram	6	2.314	2.209
Truck with ramp	3.334	2	1.884
Truck	5.054	2.654	2.1

The ratio between the maximum level of vertical vibration at the top floor, point 5 - in the centre of the room floor and at the point 4 - by the wall, is between 0.8 – 4.0 for the low-rise buildings due to the tram-induced vibrations and between 0.75-1.7 for the high-rise buildings due to the track passing the ramp. Only for a few buildings with reinforced concrete ceilings this ratio is less than 1.

2.3 Analysis of vibration levels

Vibrations generated by road or rail traffic propagate through the soil and influence both the building and its dwellers. There are international and national standards that define the vibration acceptable levels of the effects on the humans and the risk of possible damage to the buildings [2], [3], [6], [9-11]. Application of these standards has been made difficult because of inconsistency in the proposed evaluation methods and defined vibration thresholds, [7], [8].

2.3.1 Effects on buildings

Traffic-induced vibrations are rarely high enough to cause damage to buildings, but they might cause "cosmetic" damage to non structural members. Several countries have adopted standards that provide guidance on the evaluation of the effect of vibration on buildings. No such national standards have been adopted in Serbia, yet. Vibration levels measured in this study for traffic-induced vibrations were evaluated to determine their potential for building damage, using the following standards:

- British Standard BS 7385: Part 2:1993,
- German Standard DIN 4150: Part 3.

Table 2.2: Transient vibration limits for cosmetic damage in terms of PPV (mm/s) according to BS

	Type of Building	PPV (mm/s)		
		4 to 15 Hz	15 to 40 Hz	above 40 Hz
1	Reinforced or framed structures Industrial and heavy commercial buildings	50	50	50
2	Unreinforced or light framed structures Residential or light commercial type buildings	15-20	20-50	50

Table 2.3: Transient vibration limits in terms of PPV (mm/s) according to DIN 4150

PPV (mm/s)			
Type of Structure	Frequency		
	<10 Hz	10 - 50 Hz	50 - 100 Hz
Office and industrial buildings	20	20-40	40-50
Domestic houses and similar structures	5	5-15	15-20
Other buildings sensitive to vibrations	3	3-8	8-10

These standards provide guide values in terms of frequency-dependent peak particle velocity (PPV) measured in the basements near foundation walls.

The analysis of measured vibrations shows that PPVs at the foundation level do not exceed the vibration limits defined in Tables 2.2 and 2.4 for residential buildings. Particularly, maximum measured vibration amplitude at the foundation is 1.00 mm/s, which is less than any proposed limit.

2.3.2 Effects on humans

Traffic induced vibrations may be unacceptable to humans in buildings because of the annoying physical sensations and noise. The International Organization for Standardization (ISO) and several countries have published standards that provide guidance for evaluation of human response to continuous, intermittent, and transient vibrations in buildings [9]-[11]. The guidance provided by the standards is not steel clear when used for evaluation of vibrations induced by road traffic, because those vibrations have relatively short duration and complex amplitude characteristics. Hunaidi [8] first gave indication of two major difficulties in applying the standards. Firstly, there was confusion regarding the classification of these vibrations, as intermittent or transient ones. Secondly, although vibration levels are provided in the standards in terms of rms values, there is no specification regarding the integration time for rms calculation. Namely, ISO 2631 proposed one second rms, which is not applicable to short-time vibrations. Also, the thresholds for vibration effects on humans are not defined in ISO 2631-2. The ISO standard defined two methods: frequency weighted acceleration rms, and 1/3 octave band acceleration rms, but it is not clear whether it recommends them as alternative methods. These aspects of the ISO standard are quite confusing for an inexperienced user. Therefore, in order to evaluate the vibration signals measured in this study the following standards were used:

- British Standard BS 6472:1992 [1],
- German Standard DIN 4150: Part2 [5].

British Standard BS 6472:1992 shows the guide of human exposure to vibration in terms of PPV. Comparison of the records for each measuring site and source with the acceptable vibration levels given in BS 6472, shows that PPV's in vertical direction at the middle of the top floor exceed the limit for residential houses (0.282 mm/s) in the cases of 14 buildings out of 23 due to the passage of tram, and in the case of 17 out of 24 buildings due to the passage of truck over obstacle, Fig.2.8.

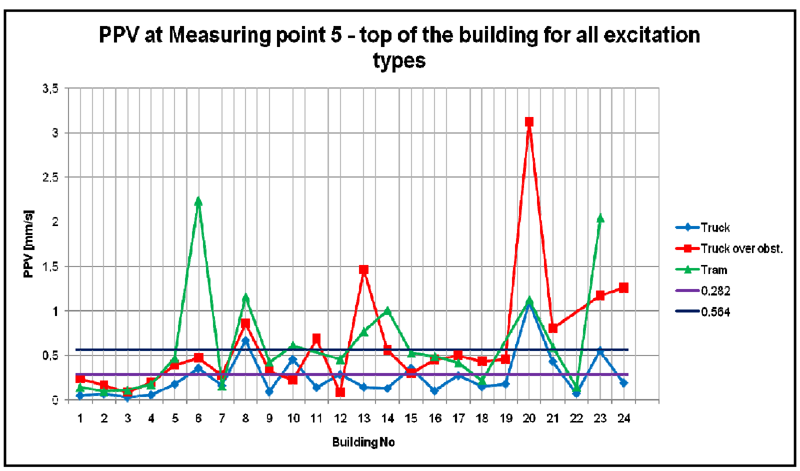


Figure 2.8 PPV's in vertical direction at the centre of the top floor due to all sources, — lower value of the perception thresholds according to BS 6472

According to DIN 4150-2, vibration intensity $KB_{f,max}$ has to be compared with the thresholds given in Table 2.4. The vertical vibrations at the centre of the room at the top floor exceed the threshold A_u=0.15 for residential houses in 15 out of 22 cases due to tram induced vibrations, Fig.2.9, and in 13 out of 23 buildings due to the truck across the ramp, Fig.2.10. The value A_o=3 for „mainly residential houses" is not exceeded in any building.

Table 2.4: Threshold for assessment of the effect of induced vibrations on human comfort

Vibration exposure location	Day			Night		
	A_u	A_o	A_r	A_u	A_o	A_r
Commercial facilities only	0.4	6	0.2	0.3	0.6	0.15
Mainly commercial facilities	0.3	6	0.15	0.	0.4	0.10
Mixed area	0.2	5	0.1	0.15	0.3	0.07
Mainly residential houses	0.15	3	0.07	0.1	0.2	0.05
Sensitive area, e.g. hospitals	0.1	3	0.05	0.1	0.15	0.05

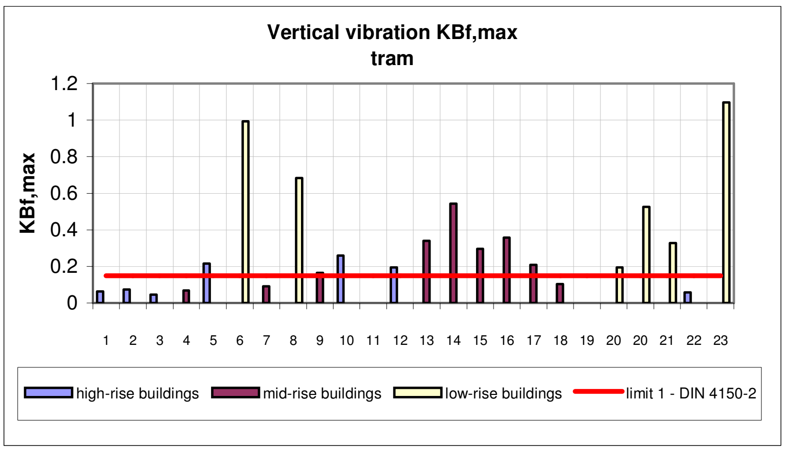


Figure 2.9 KB_{fmax} of vertical vibrations at the top floor due to the tram passage, — value of the perception threshold according to DIN 4150-2

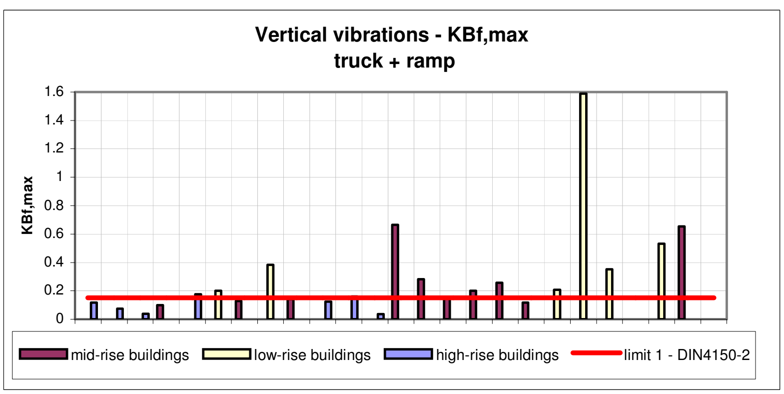


Figure 2.10 KB_{fmax} of vertical vibrations at the top floor due to the truck over ramp, — value of the perception threshold according to DIN 4150-2

2.4 Summary of measurement analysis

During the measurements of 24 buildings along the future metro line in Belgrade a large amount of data was collected and evaluated (more than 3000). Only a part of these results are presented in this paper. The general conclusions are:

- maximum PPVs are obtained due to the vibrations induced by the truck crossing the ramp and tram,
- the predominant frequencies of PPVs are in the range from 5 to 25 Hz,
- the PPVs for horizontal components of vibration are substantially less than for vertical components,

- the ratio between PPVs at the ground at the external foundation wall and at the sidewalk about 1m from the road is relatively high: 25% for low-rise buildings to 50% for mid-rise buildings,
- the ratio between PPVs at the top floor at the centre of the room and by the wall is usually larger than 1, and achieves the value 4 at low-rise buildings due to tram induced vibrations,
- vertical vibration amplitudes at foundation level do not exceed the transient vibration limits for cosmetic damage to buildings, according to both standards: BS 7385: Part 2 and DIN 4150-3,
- PPVs in vertical direction at the middle of the top floor exceed the threshold for residential houses according to BS472 for a certain number of buildings, while horizontal vibration thresholds are exceeded only for 6 buildings,
- KB_{fmax} for vibrations in vertical direction, according to the DIN 4150-2, exceeds the limit value A_u, for a certain number of buildings,
- BS472 and DIN 1450-2 give almost the same results,
- low-rise and mid-rise buildings are more sensitive to traffic induced vibrations, while high-rise buildings are less sensitive.

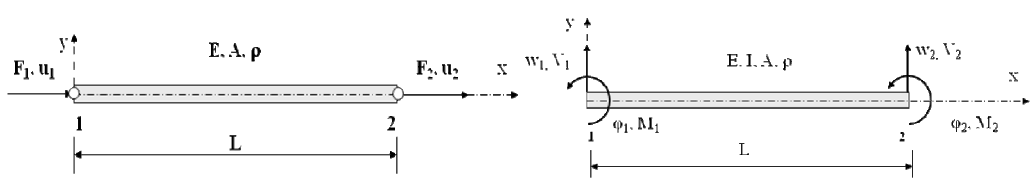
This indicates that traffic-induced vibrations, impact significantly the quality of life in the centre of Belgrade, so the effects of the new metro line should be carefully analyzed. The obtained data can be used to make prediction model to assess vibration levels of the buildings influenced by the prospective light metro traffic.

3. Numerical simulation of road traffic induced vibrations

In order to perform numerical simulation of the traffic induced vibration in buildings, a computer program for dynamic analysis of 2D frame structures in frequency domain, including soil-structure interaction, was developed. The substructure method was applied. The structure was modelled using Spectral Element Method (SEM) [5], [16], while Integral Transform Method (ITM) was used to calculate the dynamic stiffness matrix of the subsoil, [12], [14]. The influence of vibration induced by tram, truck and truck across the ramp was analyzed for 2-storey, 6-storey and 12-storey reinforced concrete two-bay frames.

3.1 Spectral element method

The 2D Spectral Element (SE) numerical model was developed to analyze wave propagation in frame structures due to traffic induced vibration, using Matlab.



a) *b)*

Figure 3.1 Bar (a) and beam (b) elements

Displacement field of spectral element was obtained by solving the partial differential equation of motion [16], for bar and beam element, respectively:

$$EA\frac{\partial^2 u}{\partial x^2} = \rho A\frac{\partial^2 u}{\partial t^2}, \qquad EI\frac{\partial^4 w}{\partial x^4} = -\rho A\frac{\partial^2 w}{\partial t^2} \tag{3.1}$$

where E, A, I, ρ, are: Young's modulus, cross-sectional area, the area moment of inertia and mass density, while $u = u(x, t)$ and $w=w(x)$ are displacement in x and y direction, respectively. Solutions of these equations are obtained as linear combination of independent exponential functions $e^{ik_j x}$ where k_j is the wave number, x is the direction along the beam and $i^2 = 1$. The dynamic stiffness matrices of the axial deformation, K_A, and bending, K_B, are frequency dependent, and can be found in literature [5], [16]. As the SE matrix is derived in frequency domain for each frequency ω, the general solution is represented by the combination of an infinite number of wave trains of different frequencies, i.e. spectral forms. Therefore, only one element can exactly represent dynamic behaviour of a beam. Dynamic response analysis needs to be carried out in frequency domain, using discrete Fourier transform [1].

3.2 Equation of motion for soil-structure system

The soil-structure-interaction effects were taken into account through substructure approach [15]. Nodes at the soil-structure interface are defined as interaction nodes (index i), while remaining nodes of the structure are defined as structural nodes (index s). Equation of motion of soil-structure system in frequency domain can be written as:

$$\begin{bmatrix} \mathbf{K}_{ss}^S & \mathbf{K}_{si}^S \\ \mathbf{K}_{is}^S & \mathbf{K}_{ii}^S + \mathbf{K}_{ii}^F \end{bmatrix} \begin{bmatrix} \hat{\mathbf{u}}_s \\ \hat{\mathbf{u}}_i \end{bmatrix} = \begin{bmatrix} 0 \\ \mathbf{K}_{ii}^F \hat{\mathbf{u}}_i^{'} \end{bmatrix}, \tag{3.2}$$

where $\mathbf{K}_{ii}{}^F$ is dynamic stiffness matrix of the soil-structure interface, $\mathbf{K}_{ss}{}^S$, $\mathbf{K}_{si}{}^S$, $\mathbf{K}_{is}{}^S$ are dynamic stiffness sub-matrices of the structure obtained using SE, $\hat{\mathbf{u}}_s$ and $\hat{\mathbf{u}}_i$ are sub-vectors of displacement amplitudes at structural (s) and interaction nodes (i), while $\hat{\mathbf{u}}_i^{'}$ is vector of traffic-induced ground motion amplitudes.

3.3 Dynamic stiffness matrix of rigid foundations

Dynamic stiffness matrix (impedance functions matrix) of a rectangular massless rigid foundation $\mathbf{K_o}$, resting on the soil surface, Fig.3.2, was calculated from dynamic stiffness matrix of flexible foundation $\mathbf{K}_{ii}^F$, Fig. 3.3, by simple kinematic transformation:

$$\mathbf{K}_o = \mathbf{a}^t \mathbf{K}_{ii}^F \mathbf{a} = \begin{bmatrix} k_h & 0 & k_{hr} \\ 0 & k_v & 0 \\ k_{rh} & 0 & k_r \end{bmatrix}, \ \mathbf{a} = \begin{bmatrix} \mathbf{a}_1 \\ \dots \\ \mathbf{a}_i \\ \dots \\ \mathbf{a}_{nxn} \end{bmatrix}, \quad \mathbf{a}_i = \begin{bmatrix} 1 & 0 & -y_i \\ 0 & 1 & x_i \end{bmatrix} \tag{3.3}$$

where **a** is kinematic matrix, and nxn is number of interaction nodes. For surface foundations, coupling terms k_{hr} were neglected.

The dynamic stiffness matrix of a flexible foundation on the layered half space was obtained by inverting the dynamic flexibility matrix, $\mathbf{K}_{ii}^F = \mathbf{F}_{ii}^F$. The elements of dynamic flexibility matrix represent the nodal displacements at the surface due to corresponding harmonic forces of unit amplitude, Fig. 3.3. These elements were obtained using ITM. By a threefold *Fourier Transform* with regard to x∘–•kx, y∘–•ky and t∘–•ω one scalar and two vectors body wave equations were transformed into the ordinary differential equations regarding the z-direction in wave number domain. The solution of these equations allows to derive macro-element relations for each layer between the stress and displacement at the top and bottom boundary of the layer in transformed domain [14]. The unknown integration constants were obtained from the boundary conditions at the interface between the layers of half space. At the upper surface of the top element the boundary conditions of the half space must be fulfilled, as well as the Sommerfeld's radiation condition if the bottom element goes to infinity.

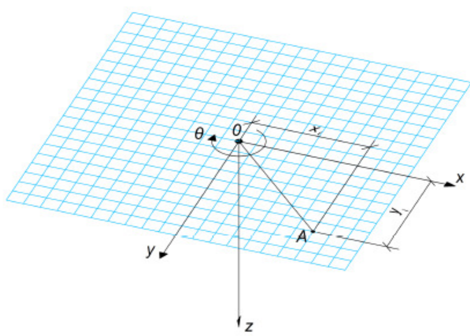


Figure 3.2 Rigid foundation

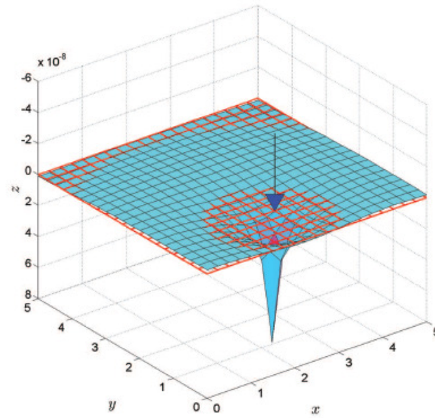


Figure 3.3 Flexible foundation

The obtained response was transformed from frequency to time domain by *Inverse Fourier Transform*. The ITM procedure scheme is shown in Fig. 3.4.

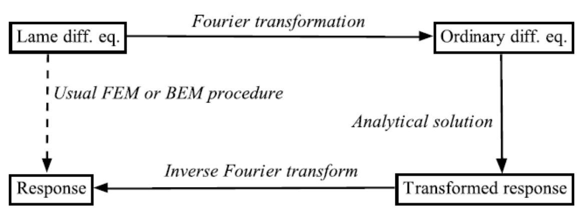


Figure 3.4 ITM procedure scheme

3.4 Numerical example

The numerical analysis of traffic-induced vibrations on three typical low-rise, mid-rise and high-rise concrete 2D frames was carried out. Two-storey, six-storey and twelve-storey frames have two bays, 4 m width, Fig. 3.5. The story height is 3.5m for the first floor and 3 m for all other floors. Mass of the each floor, equal to 9 t, was added continuously to the mass of the beams. Geometrical properties of the frame members are given in Table 3.1. Structural damping coefficient is 5%. The frames are founded on rigid and massless rectangular footings, 2x2 m size. The footings rest on elastic homogeneous half space, whose properties are given in Table 3.1

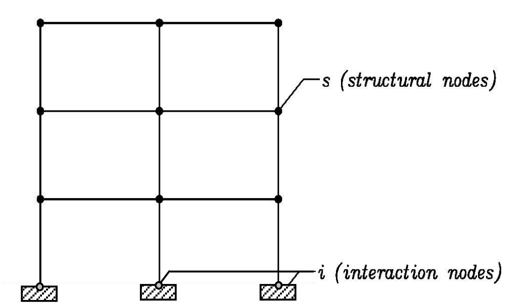


Figure 3.5 Soil-structure system

Table 3.1: Properties of a half-space

Material properties of the half space	
mass density	2000 kg/m^3
Poisson's ratio	0.33
shear waves velocity	100 m/s

Table 3.2: Geometrical properties of the frames

Frame	*Columns*		*Beams*
	External	*Internal*	
Two storey	20x30 cm	25x30 cm	23x40 cm
Six storey	20x30 cm	25x50 cm (1-2 floor) 25x40 cm (3-5 floor) 25x30 cm (6th floor)	
Twelve storey	25x40 cm (1-5 floor) 20x35 cm (6-8 floor) 20x30 cm (9-12 floor)	25x80 cm (1-2 floor) 25x70 cm (3-4 floor) 25x60 cm (5-7 floor) 25x50 cm (8-10 floor) 25x40 cm (11-12 floor)	

3.4.1 Numerical results

Frames were subjected to the ground displacements in horizontal and vertical directions, obtained from ground velocities measurements at the building foundation due to the tram induced vibrations, Figs. 3.6a-3.7b. In order to study the effect of soil-structure interaction on dynamic response, analysis was carried out for the fix-based and flexible-based frames. Obtained displacement and velocity envelopes are presented in Figs. 3.8-3.13.

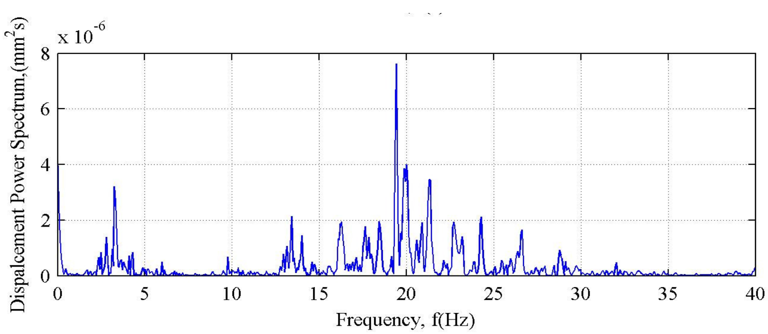


Figure 3.6a Power spectrum of horizontal ground displacement (tram, v=20 km/h, distance to track 11 m)

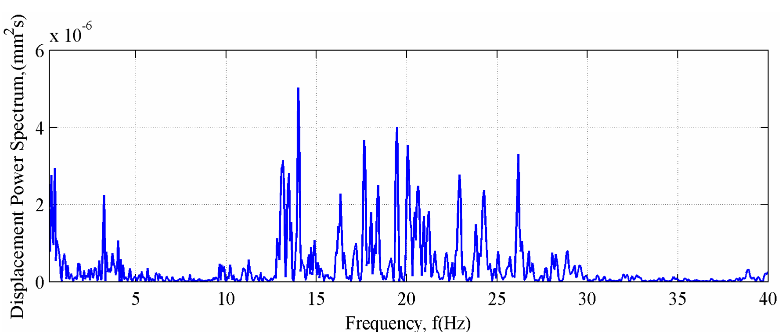


Figure 3.6b Power spectrum of vertical ground displacement (tram, v=20 km/h, distance to track 11 m)

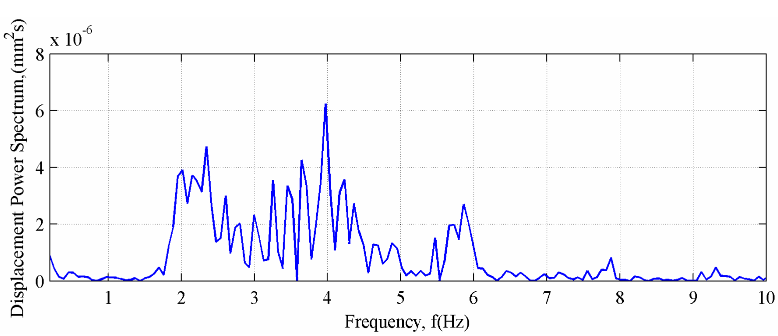


Figure 3.7a Time history of horizontal ground displacement (truck across a ramp, v=50 km/h, distance to road 11 m)

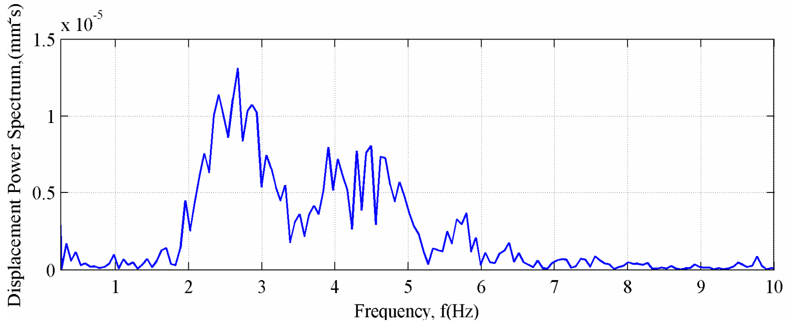


Figure 3.7b Power spectrum of vertical ground displacement (tram, v=20 km/h, distance to track 11 m)

The predominant frequencies of truck-induced vibration fell in the narrow range between 2 and 6 Hz. Predominant frequencies of tram-induced vibration, however, were spread over a wider frequency range between12 and 27 Hz.

The natural frequencies of investigated frames for horizontal and vertical mode shapes are given in Tables 3.3 and 3.4 for fix-based and flexible-based structures. The flexibility of the base reduced natural frequencies of frames. This is especially pronounced for the vertical vibration modes, due to the fact that ratio between frame stiffness and soil stiffness in vertical direction is much higher than corresponding stiffness ratio in horizontal direction. Consequently, vertical dynamic responses of fixed base frames differ from the dynamic responses of flexible based structures.

Table 3.3: Natural frequencies for horizontal mode shapes

Frame storey	*Natural frequencies (fixed-base frame), Hz*					*Natural frequencies with SSI, Hz*				
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
2	2.37	7.49				2.29	7.40			
6	1.08	3.22	5.48	7.95	10.71	1.01	3.11	5.36	7.81	10.55
12	0.62	1.81	3.21	4.7	6.34	0.56	1.74	3.11	4.55	6.14

Table 3.4: Natural frequencies for vertical mode shapes

Frame storey	*Natural frequencies (fixed-base frame), Hz*					*Natural frequencies with SSI, Hz*				
	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
2	15.79	18.06	19.31	22.21	39.53	15.44	21.68	50.8	57.5	63.0
6	12.22	13.41	16.68	18.34	19.25	10.55	12.8	16.24	18.09	18.94
12	8.11	13.83	16.74	18.13	18.83	7.9	11.58	13.57	15.93	16.61

Horizontal vibrations: Truck crossing a rubber ramp produces larger horizontal displacements than tram in all frames, and higher horizontal velocities in 6-storey and 12-storey frames, since the passed by frequencies of the truck fall into the frequency range between 2-5 Hz, affecting the dominant horizontal vibration modes of all frames. Two-storey frame experiences the largest horizontal displacements and twelve-storey frame the lowest horizontal displacements because the fundamental vibration mode of two-storey frame (2.37 Hz) falls in the dominant frequency range, while for the six- and the twelve-story frames 2nd and 3rd modes are affected, respectively. Consequently, horizontal displacement at the top floor of the two-storey frame is highly amplified. Horizontal velocities are higher for truck-induced vibrations than for tram-induced vibrations in 2- and 6-story frames, while tram-induced vibrations caused higer velocities of 12-storey frame, due to the stated relation between the passed by vehicle frequencies and vibration modes of structures.

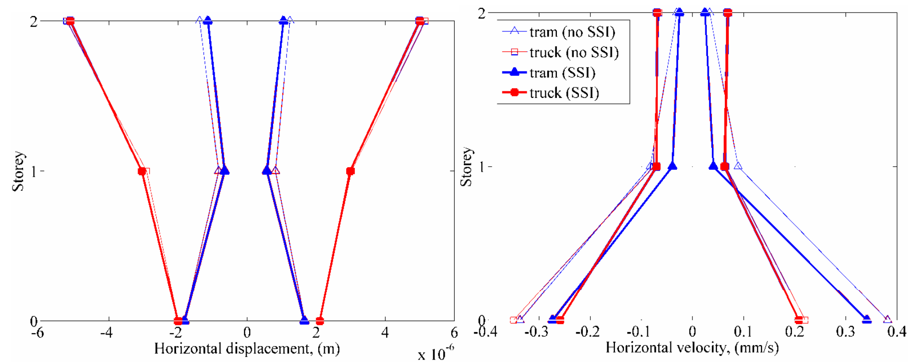


Figure 3.8 Horizontal displacement and velocity envelopes of two-storey frame

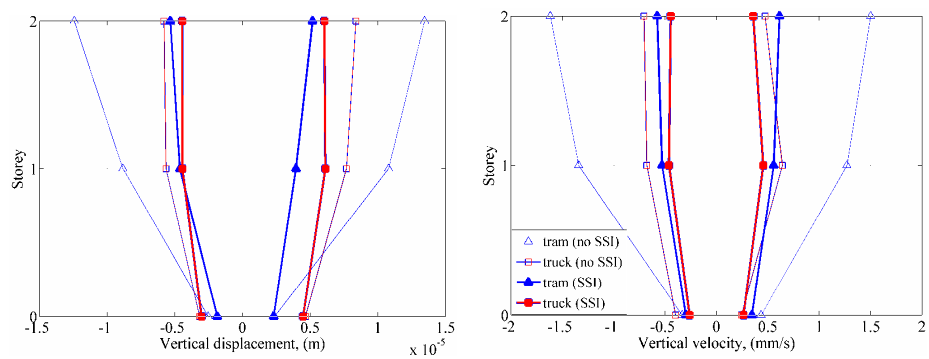


Figure 3.9 Vertical displacement and velocity envelopes of two-storey frame (middle point on the beam)

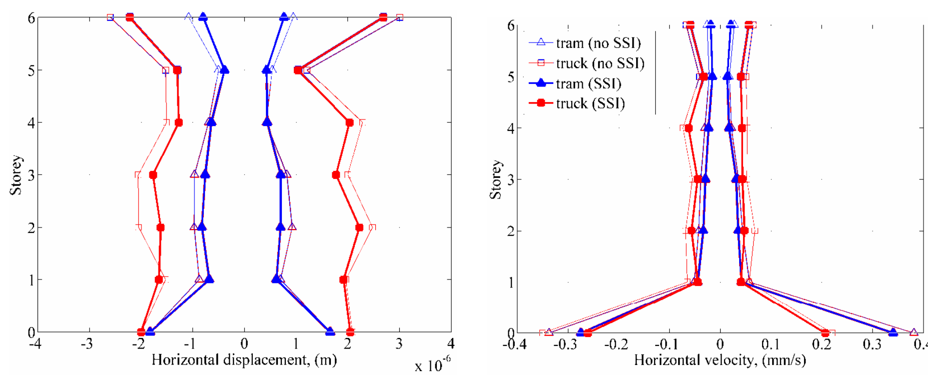


Figure 3.10 Horizontal displacement and velocity envelopes of six-storey frame

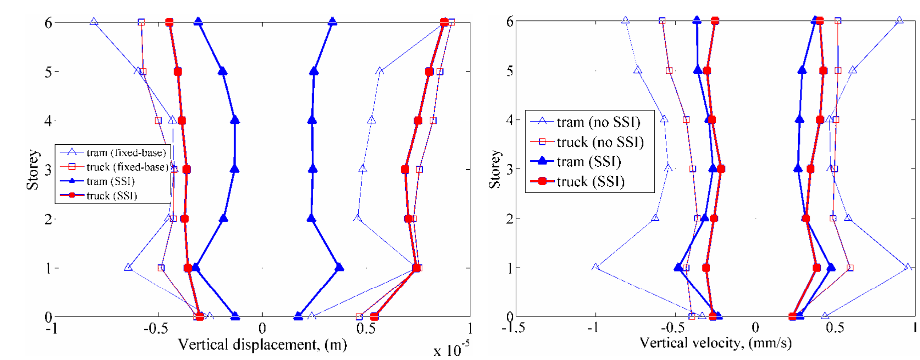


Figure 3.11 Vertical displacement and velocity envelopes of six-storey frame (middle point on the beam)

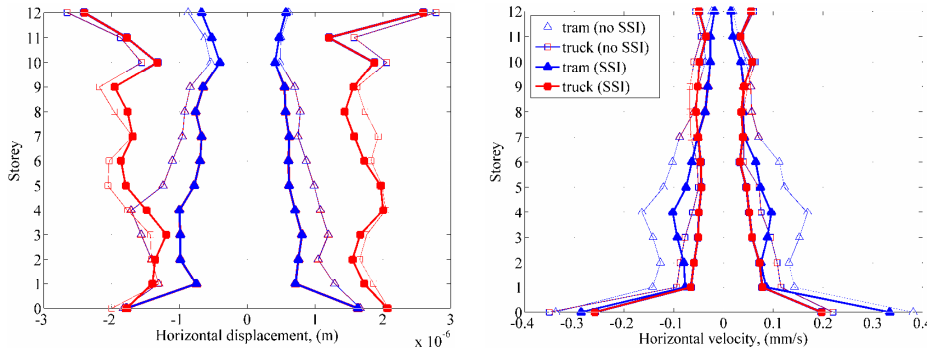


Figure 3.12 Horizontal displacement and velocity envelopes of twelve-storey frame

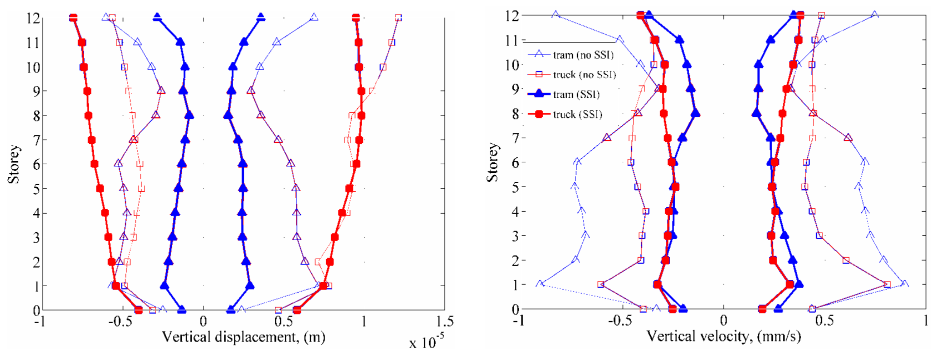


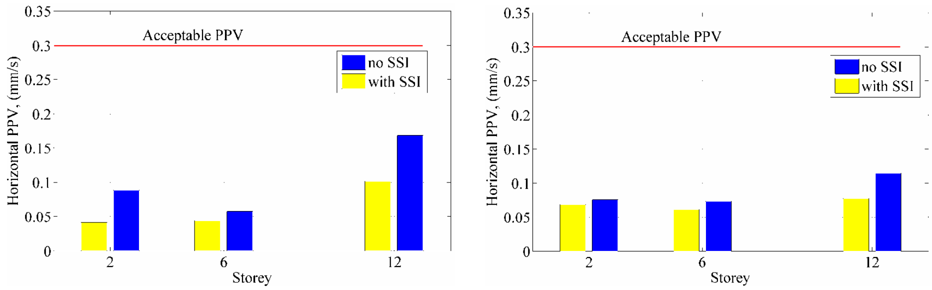
Figure 3.13 Vertical displacement and velocity envelopes of twelve-storey frame (middle point on the beam)

Vertical vibrations: The largest vertical displacements occur at the midpoint of the beam at the top floors. Vertical dynamic responses of all frames are influenced by lower vertical vibration modes. Larger vertical displacements and velocities are induced by the tram than by the truck across a ramp, because the frame natural frequencies fall into the range of predominant frequencies for tram-induced vertical vibrations (13-20 Hz). Predominant frequency of vertical vibration induced by the truck is between 2-6 Hz, causing only larger vertical displacements in the twelve-story frame.

Soil–structure interaction (SSI) generally alters vertical response of frames. Vertical displacements and velocity envelopes have much lower values than the corresponding values for fixed base frames due to the radiation damping. This effect is more pronounced for tram-induced vibrations. The only exception to that rule is the truck-induced vertical displacements of twelve-story frame, where soil flexibility caused higher displacement amplitudes than the case of fix based structure. The SSI reduced horizontal vibrations but, generally, less than vertical ones.

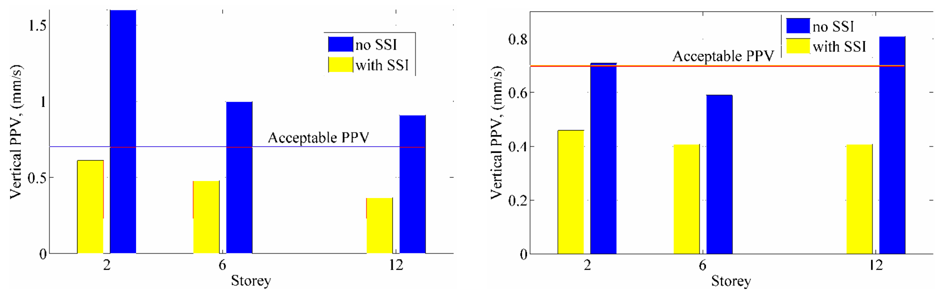
Maximum horizontal and vertical velocities, peak particle velocity (PPV), of all frames are presented in Figures 3.14 and 3.15. Horizontal vibrations do not exceed the acceptable limits for human perception in terms of PPV, according to BS: 6472. Vertical PPV for fix based frames is larger than acceptable vertical vibration limits. PPV is significantly decreased when SSI is taken into account, and it is below the acceptable level according to BS.

The vibration intensity $KB_{f,max}$, was calculated for vertical vibrations at the top floor according to DIN 4150-2, Figs. 3.16 and 3.17. $KB_{f,max}$ exceeds the limit value A_u=0.15 for residential area, in all fix-based frames, Fig. 3.16. When SSI is taken into account, the limit is exceeded in the cases of the two-storey frame due to the tram induced vibration and the twelve-story frame due to the truck across the ramp induced vibration, Fig.3.17.



a) b)

Figure 3.14 Peak particle velocities for horizontal vibrations induced by tram (a) and truck across the ramp (b)



a) b)

Figure 3.15 Peak particle velocities for vertical vibrations induced by tram (a) and truck across the ramp (b)

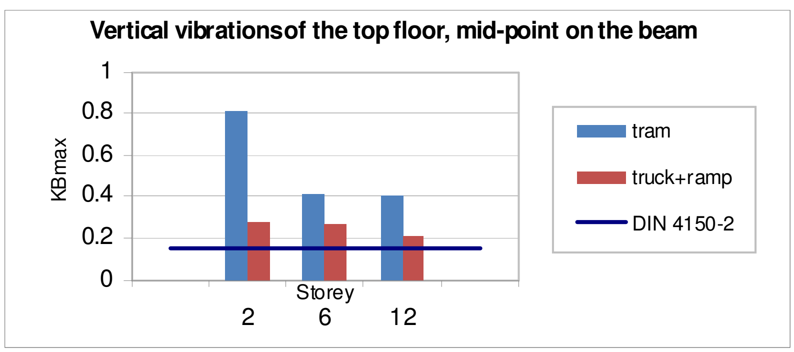


Figure 3.16 Peak particle velocities for vertical vibrations induced by tram (a) and truck across the ramp (b) (no SSI)

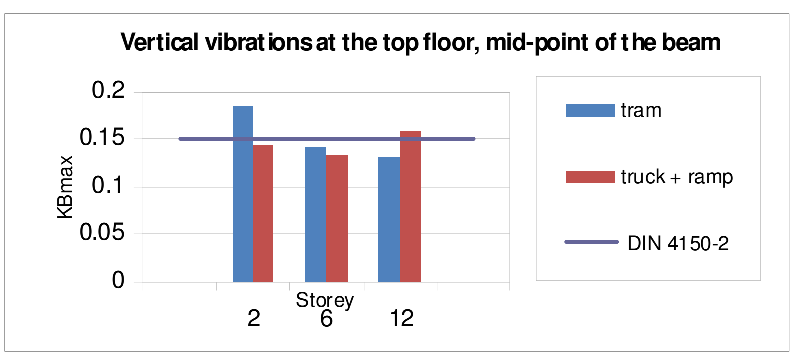


Figure 3.17 Peak particle velocities for vertical vibrations induced by tram (a) and truck across the ramp (b) (with SSI)

3.4.2. Summary of numerical modelling

Foundation displacements induced by tram traffic and heavy truck crossing 3 cm thick rubber ramp were used as input ground motion for three frame structures of different heights, with fixed- and flexible base. The vibration analysis of frames was carried out in the frequency domain using Spectral Element and substructure approach. After the vibrations analysis the following conclusions have been reached:

- vibrations depend on the relation between natural frequencies of the structure and predominant frequencies of the vehicle; for example, tram produced higher vertical vibrations in low- and mid-rise frames, truck in high-rise frame
- horizontal vibrations are less than vertical and generally do not exceed limit values according to BS7385 and DIN 4150-3,
- vertical vibrations are generally larger than limit values defined in BS6472 and DIN4150-2 for fix-based structure,
- SSI reduced vibration amplitudes; the reduction depends on soil-structure stiffness ratio,
- vertical vibration amplitudes are more reduced due to SSI than horizontal ones,
- the numerical analysis generally confirms the measurement results.

4 Conclusion

Traffic induced ground vibrations were measured along the future metro line in Belgrade, and some of the results are presented for 24 buildings in King's Aleksandar Boulevard in Belgrade. Vibrations induced by the existing tram traffic and heavy truck crossing 3 cm thick rubber ramp were analyzed. Traffic-induced vibrations were significantly lower than the limit values for building damage specified by BS7385 and DIN4150-3 standards. For most data recorded in low-rise and mid-rise buildings perception threshold defined by BS6472 for peak particle velocity and DIN 4150-2 for KB_{fmax} was exceeded. This indicates that traffic-induced vibrations impact significantly the quality of life in urban cities.

Simple transfer relation can be used for a rough prediction of velocity amplification inside a building from vibrations measured on the internal foundation wall. For more accurate estimates of vibration levels at a particular site, the transfer functions should be used. The first calculation of transfer functions using Matlab has shown great discrepancy between different sources at the same site which required further analysis.

The numerical analysis of three low- mid- and high-rise reinforced concrete frames shows great dependency between natural frequency of structure and predominant frequency range of vehicle. If the frequencies of low modes lie in the vehicle predominant frequency range then vibration can be significant. The SSI generally reduces the vibrations of a structure. The level of reductions depends on soil-structure stiffness ratio. It should be pointed out that using substructure method influence of soil conditions on traffic-induced ground vibration could not be taken into account.

In order to have better numerical simulation of traffic-induced vibration in buildings the 3D frame space model with spectral plate elements has been developed. The passage of waves through the surrounding soil due to the moving vehicle will be taken into account simultaneously using ITM method.

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