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RESPONSE ANALYSIS OF BUILDING LOADED BY GROUNDBORNE TRANSIENT VIBRATION

Daniel Makovička[1], **Daniel Makovička, Jr.**[2]

[1] Czech Technical University in Prague, Klokner Institute
CZ16608 Praha 6, Šolínova 7, Czech Republic
e-mail: makovic@klok.cvut.cz

[2] Static and Dynamic Consulting
CZ28401 Kutná Hora, Šultysova 170, Czech Republic
e-mail: d.makovicka@makovicka.cz

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Abstract. *By sitting of a building in the vicinity of underground tube structure the effect of train operation excites the groundborne vibration. This vibration as a technical seismicity propagates through subsoil to the building foundations in the vicinity of the source. The solution of vibration transfer from the subsoil environment to the building structure is demonstrated using the example of a multistorey reinforced concrete building, founded on large diameter piles mutually connected with the lower foundation plate by reinforcement. On top of this plate an antivibration layer of rubber has been designed. Above the rubber there is an upper foundation plate in which the cast-in-place skeleton building structure is constrained. The elastic rubber course separates upper and lower parts of foundation plate and single footings. The structure is loaded by the groundborne vibrations from the rail systems of underground. The actual history of dynamic load measured on the pile heads was used as an input data for vibro-base insulation design and dynamic analysis of the structure. The structure model takes into account the individual storeys, broken down into the floor, foundation and roof slabs, columns, load-bearing walls and peripheral and interior girders. The layer of rubber was considered as the elastic subsoil of the Winkler-Pasternak model below the whole area of the upper part of the foundation plate and as the elastic support for columns and walls above the piles on the upper foundation plate level. The rubber stiffness in the theoretical model takes into account the type of plates used as well as the mutual superposition of surface and point support on the upper foundation plate level. The mass of the floor and foundation plates includes the masses of the non-load-bearing components (thin partitions, floorings, etc.) as well as the equivalent of the useful loads of floors, roof and terraces. The prediction of floor vibrations is determined and compared with non-isolated state of the building. The vibro-base isolated structure fulfils the standard requirements for limit vibration level for residential structure.*

1 INTRODUCTION

The dynamic effects of subsurface traffic propagating through the ground environment into the ambient buildings of urban agglomerations have been acquiring ever increasing importance. Construction firms try to use the areas in the proximity of underground lines because of their lucrative location, usually for residential construction. It is these structures erected in the proximity of underground tunnels or directly above them in the case of shallow tunnels that are threatened by vibrations from underground traffic.

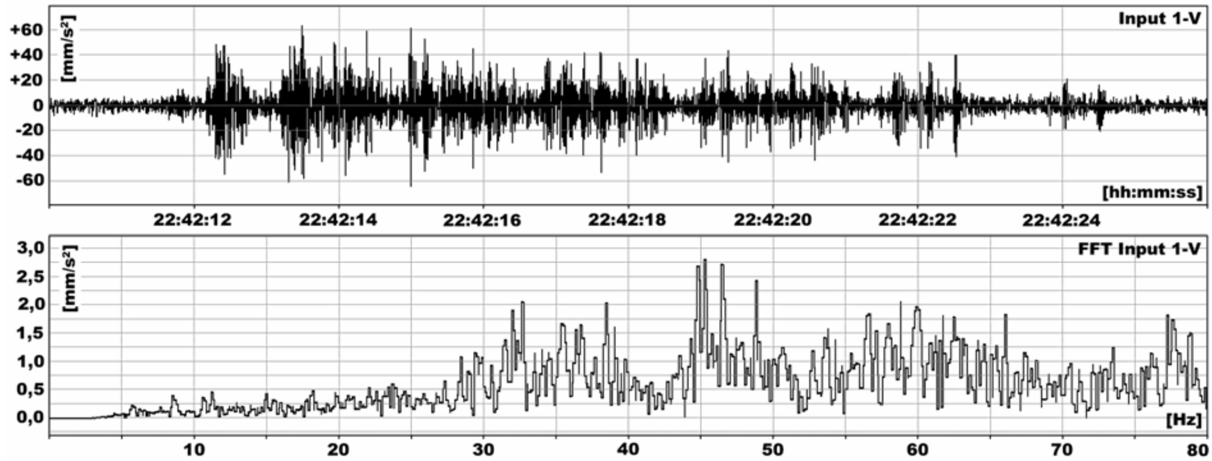

Figure 1: Vertical vibration of pile head excited by a train passing through a tunnel Prague line C (the whole course – up, frequency spectrum – bottom).

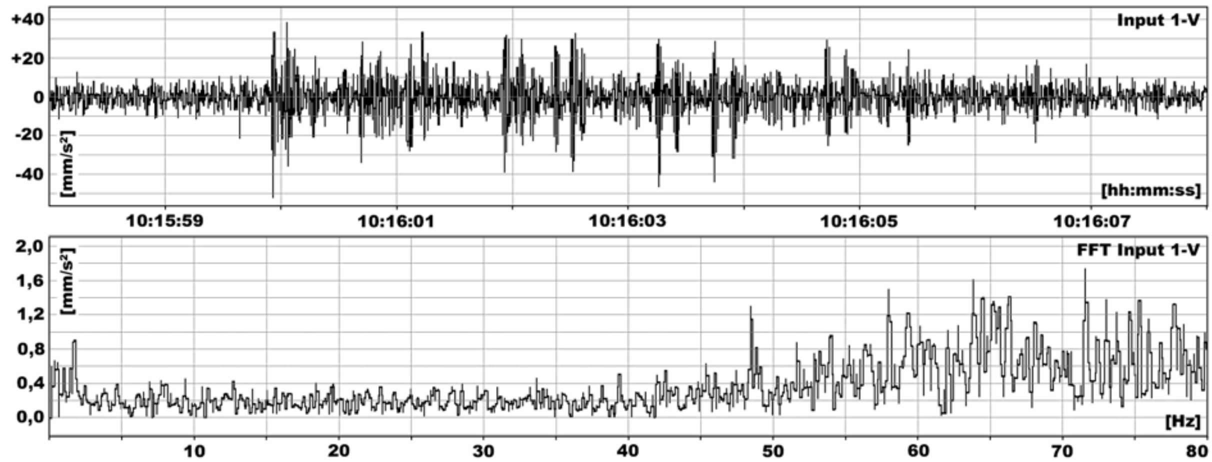

Figure 2: Vertical vibration of pile head excited by a train passing through a tunnel Prague line B (the whole course – up, frequency spectrum – bottom).

Trains running through underground tunnels produce vibrations (Figure 1 and Figure 2) which, together with the vibrations from a wide range of constituents of the underground railway, such as ventilation fans and escalator drives, propagate from the source to more distant structures. As a rule, these vibrations propagate into building foundations at the foundations/subgrade interface. Vibrations produced by subsurface traffic usually do not threaten the safety of structures. Nevertheless, they may be significant because of their undesirable impacts on people living or working in the residential or office parts of the building, especially due to their tuning.

2 LOADING EFFECT OF UNDERGROUND TRAFFIC

The character of vibrations depends on their parameters at their source (compare Figure 1 versus Figure 2), i.e. the character of train motion, the structure and occupancy of the rolling stock, the geometry and characteristics of the permanent way (above all, the fastening of the rails, etc. – compare Figure 1 and 2 versus Figure 3), the structure of the tunnel or station, the parameters of the equipment of the tunnel or station, etc.

The magnitude of the vibrations is influenced not only by the vibration parameters at the source, but also by the composition of the geological environment in the proximity of the underground railway, i.e. the route from the source to the threatened structure. Last but not least, the magnitude of these vibrations may be increased or damped by the actual execution of the structure loaded by them.

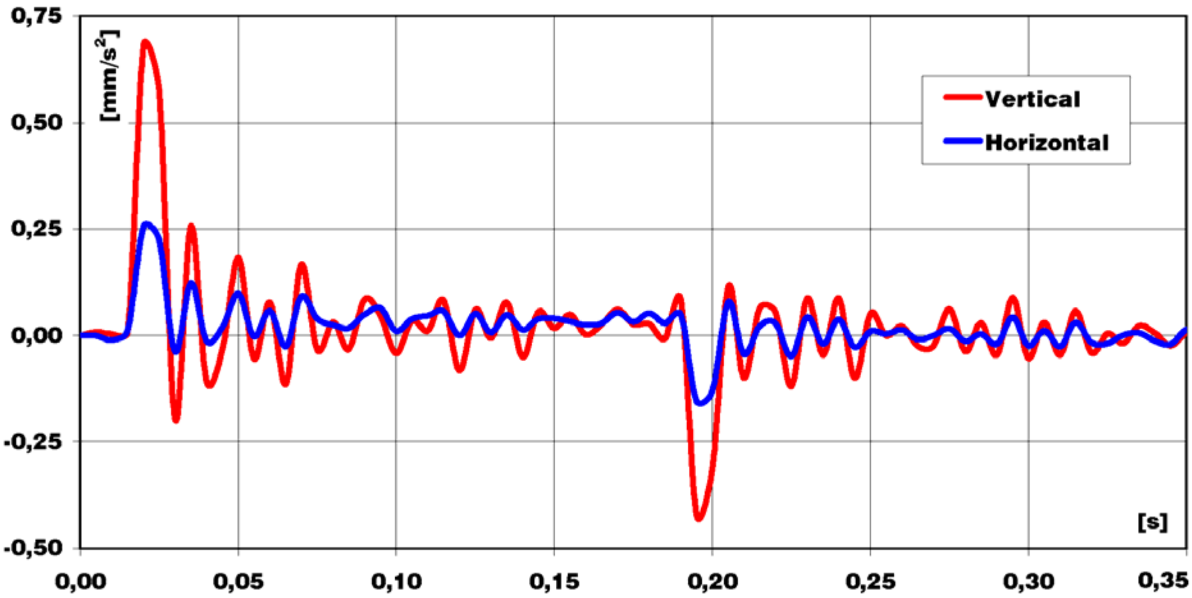

Figure 3: Vibration of pile heads excited by a train passing over the boundary between the under-ground and above-ground bridge part of the tunnel structure.

When planning the correct measures for a structure that we intend to protect against excessive vibrations, we therefore need to know the amplitude level and frequency structure of the vibrations which will propagate from the underground into the building.

However, the measured real characteristics of the vibrations may show considerable mutual differences, because the magnitude of the vibrations and their frequency structure depend not only on the general parameters (train design, permanent way, structures of stations and tunnels, etc.) but also on local parameters on the site (particularly the composition of the geological environment, foundation design, etc.).

Therefore, a responsible designer of measures for reducing vibration transfer into the structure to be protected needs, first of all, to perform vibration measurements on site, and to evaluate them, preferably at the foundation base level. These measurements produce typical histories of vibrations affecting selected parts of the structure (such as pile heads at the foundation base – compare Figure 1 and 2 versus Figure 3), which can be considered as the dynamic load of the future or existing structure at its foundation level. This vibration load has a non-stationary character.

3 ELASTIC SUPPORT OF THE STRUCTURE AT ITS FOUNDATION LEVEL

An effective method for reducing the vibration level of the protected structure as a whole with reference to its foundation structures (plate, piles, strips, etc.) is to spring it from the foundations. This springing is usually effected by placing the whole upper part of the structure on individual springs or sprung layers.

The effectiveness of the springing is determined by the frequency tuning of the sprung structure. The lower the tuning of the structure based on springs (the lower the dominant natural frequencies), the greater the decrease of the higher vibration frequencies and acoustic frequency effects propagating into the structure from its geological environment.

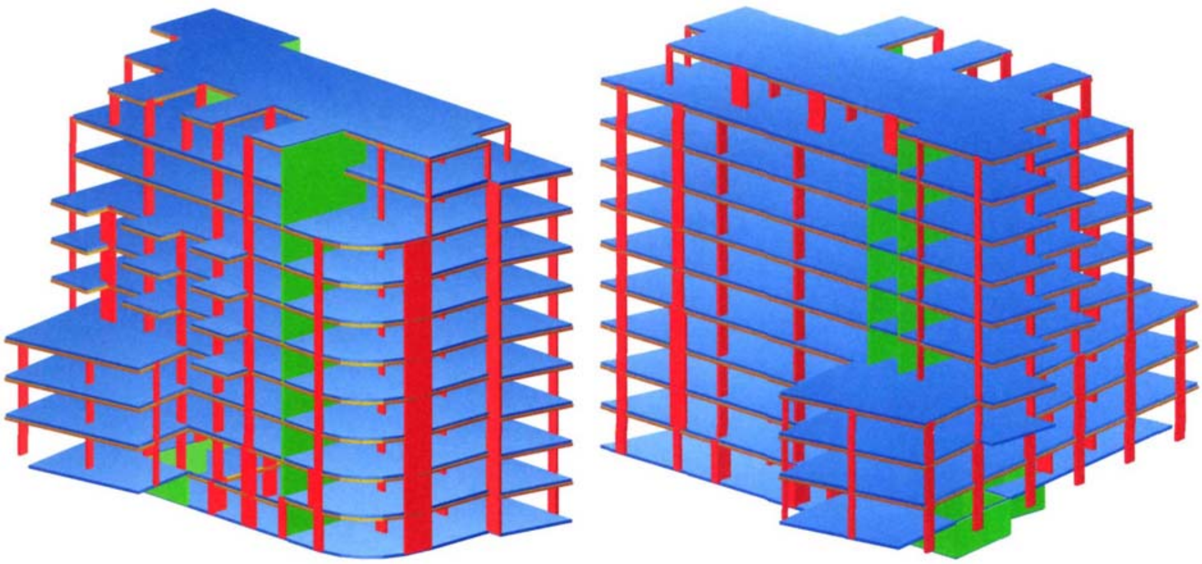

Figure 4: Calculation model, Southwest view (left) and Northeast view (right).

The solution of vibration transfer from the subsoil environment to the building structure is demonstrated using the example of a multistorey reinforced concrete building, founded on large diameter piles mutually connected with the lower foundation plate by reinforcement. On top of this plate an antivibration layer of rubber has been designed. Above the rubber there is an upper foundation plate in which the cast-in-place skeleton building structure is constrained.

Consequently, the elastic layer of rubber consistently separates the lower and the upper parts of the foundation plate and the lower and the upper parts of the self-supporting footings (horizontal layers of rubber) as well as all vertical structural members below ground level from the ambient environment (vertical, slanting and horizontal layers of rubber surrounding the columns in the soil, outside walls below ground level, the upper part of footings or foundation strips in contact with the soil backfill).

A theoretical model of the building (Figure 4), together with a lay-out of the rubber distribution in the foundation part (Figure 5), takes into account the individual storeys, broken down into the floor, foundation and roof slabs, columns, load-bearing walls and peripheral and interior girders.

The layer of rubber was considered as the elastic subsoil of the Winkler-Pasternak model below the whole area of the upper part of the foundation plate and as the elastic support for columns and walls above the piles on the upper foundation plate level. The rubber stiffness in the theoretical model takes into account the type of plates used as well as the mutual superposition of surface and point support on the upper foundation plate level. The mass of the floor and foundation plates includes the masses of the non-load-bearing components (thin partitions, floorings, etc.) as well as the equivalent of the useful loads of floors, roof and terraces.

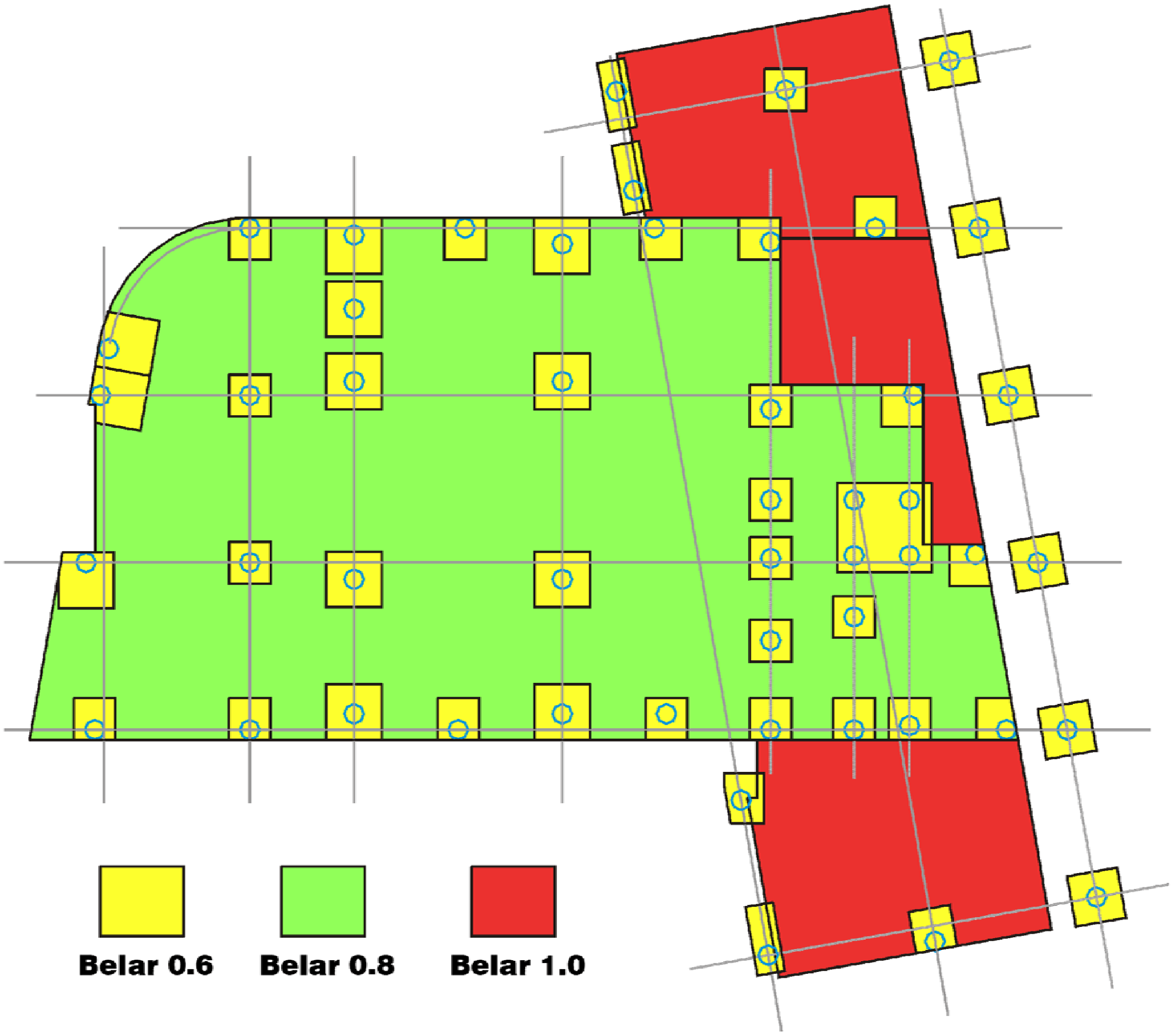

Figure 5: Design of rubber distribution (of various rubber types BELAR).

The simplifications applied to the model dynamic loads can be summed up as follows: the maximum measured vibration history observed on the most highly vibrating pile was used; its maximum amplitude scale was selected in such a way as to make the dynamic load intensity drop (for a homogeneous earth environment between the piles) exponentially with the distance from the vibration source.

The dynamic load, i.e., the vibrations, was introduced into the model simultaneously and with the identical phase; in reality, the loads applied to individual piles will be phase-displaced and their influence on the building structure will be lower. The magnitude of the measured dynamic load does not take into account the additional load which will be applied to the piles by the future building.

After mutual stiffening of the pile heads by the future foundation slab, this change of loading and mutual connection of the piles will result in a reduction of the transfer of the excitation signal propagating through the soil, and in a reduction of the differences in excitation level of the individual piles; it is estimated that this simplification may influence the response of the structure up to +/- 20%.

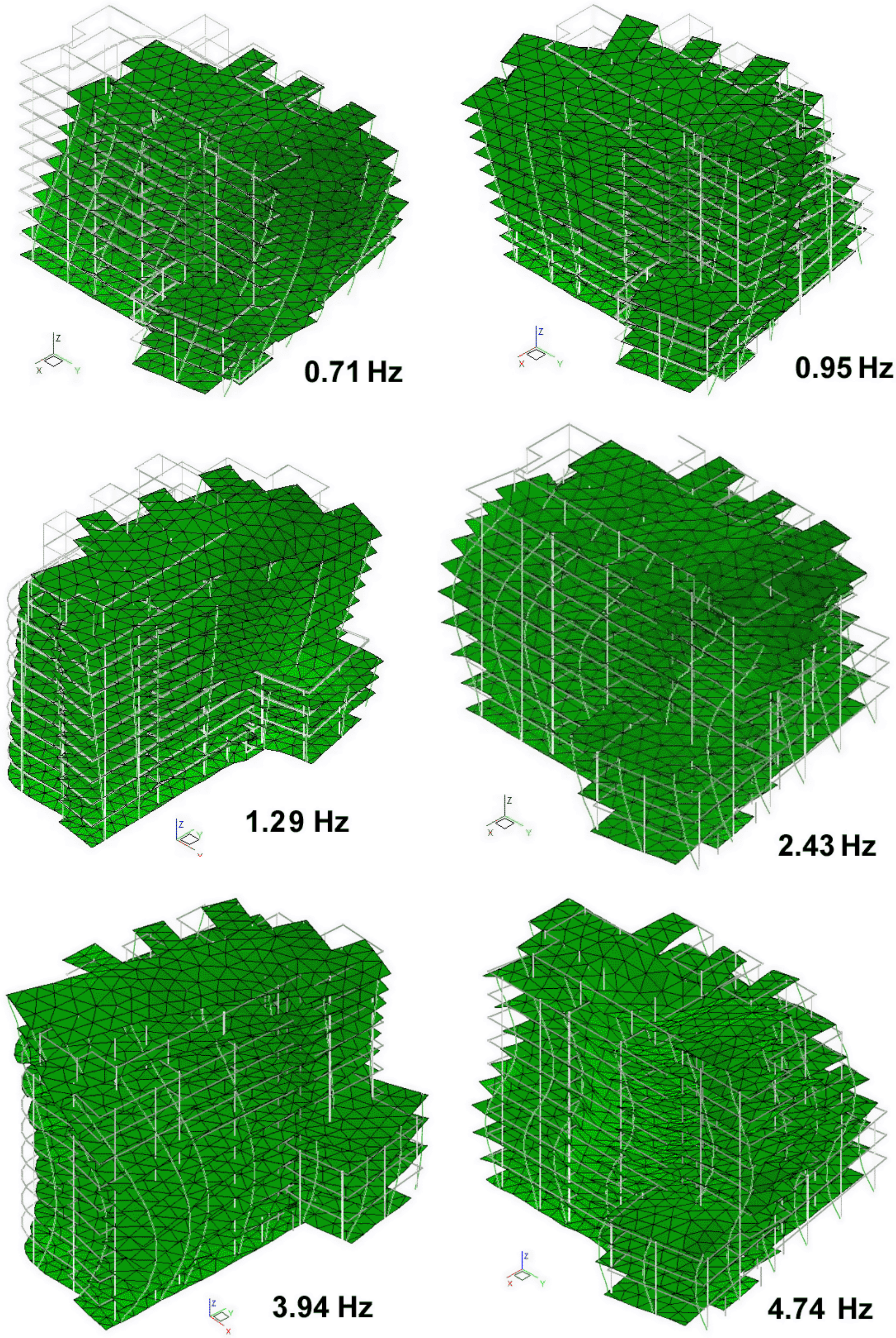

Figure 6: The lowest six natural vibration modes.

The mechanical characteristics of the antivibration rubber layer were determined by laboratory tests of 500×500×25 mm samples that were used to form the vibration-resistant layer. The rubber blocks (slabs) are butt-jointed (not interlocked) in a single layer with 3~5 mm joints enabling the rubber to buckle, thus assuring identical conditions of deformability and, consequently, stiffness corresponding to the conditions at the foundation base.

The specification of the distribution and rubber types used was based on repeated response computations so as to make the stiffness of the elastic rubber layer approximately the same throughout the foundation base and to keep the tuning of the rubber-mounted building structure within the low frequency range. An example of rubber distribution in a horizontal joint is shown in Figure 5.

4 PREDICTION OF VIBRO-BASED STRUCTURE RESPONSE

The natural vibrations were computed for the analyzed building structure. For the dynamic response to the effects of external actions (traffic), the lowest possible tuning of the rubber-mounted structure is decisive. This manifests itself, on the one hand, by flexural vibrations of the vibro-based building in the environs of 1 Hz, and, on the other hand, by vertical and horizontal translate vibrations of the building as a whole or by torsion vibrations. The lowest six vibration modes are shown in Figure 6.

Not only the basic natural vibration modes but also the higher natural vibration frequencies of the individual storeys, possibly columns and walls, balconies, etc., appear in the computation, which makes the response of the building on each storey slightly different (higher, lower, possibly with antinodes on different sites).

Vibrations of the building produced by underground traffic were determined by the histories of the forced vibrations. In addition, the envelopes of the maximum values of the transient vibrations in the displacements were evaluated and documented for selected under-ground and above-ground storeys in Figure 7.

The history of the kinematic excitation in normalized form, used in the capacity of the load, is shown in Figure 8 together with the histories of the response of the structure. The computed vibration histories reveal that the vibrations due to underground train traffic introduced into the structure are felt particularly in the lowest storey.

The most intensive vibrations can be observed in the proximity of columns and structural parts situated on the underground side. With increasing height, this excitation mode will manifest itself by the vibrations of the building in one of the natural frequencies of the structure.

More significant influence of vibration is limited to the lowest two or three storeys, in most cases. In the higher storeys, the time characteristic of the vibrations is divided into lower frequencies. Another element reducing the vibration level in the individual storeys are the non-load-bearing partitions, floating floors, carpet floorings, etc.; an analysis of these factors, however, is beyond the range of this paper.

An observation of the response computation during vertical versus horizontal excitation reveals that the horizontal excitation level is lower than the vertical excitation level - according to the measurements, approximately twice as low. Moreover, the response to horizontal excitation is of very low frequency, as a rule, and it is also damped faster than in case of vertical excitation.

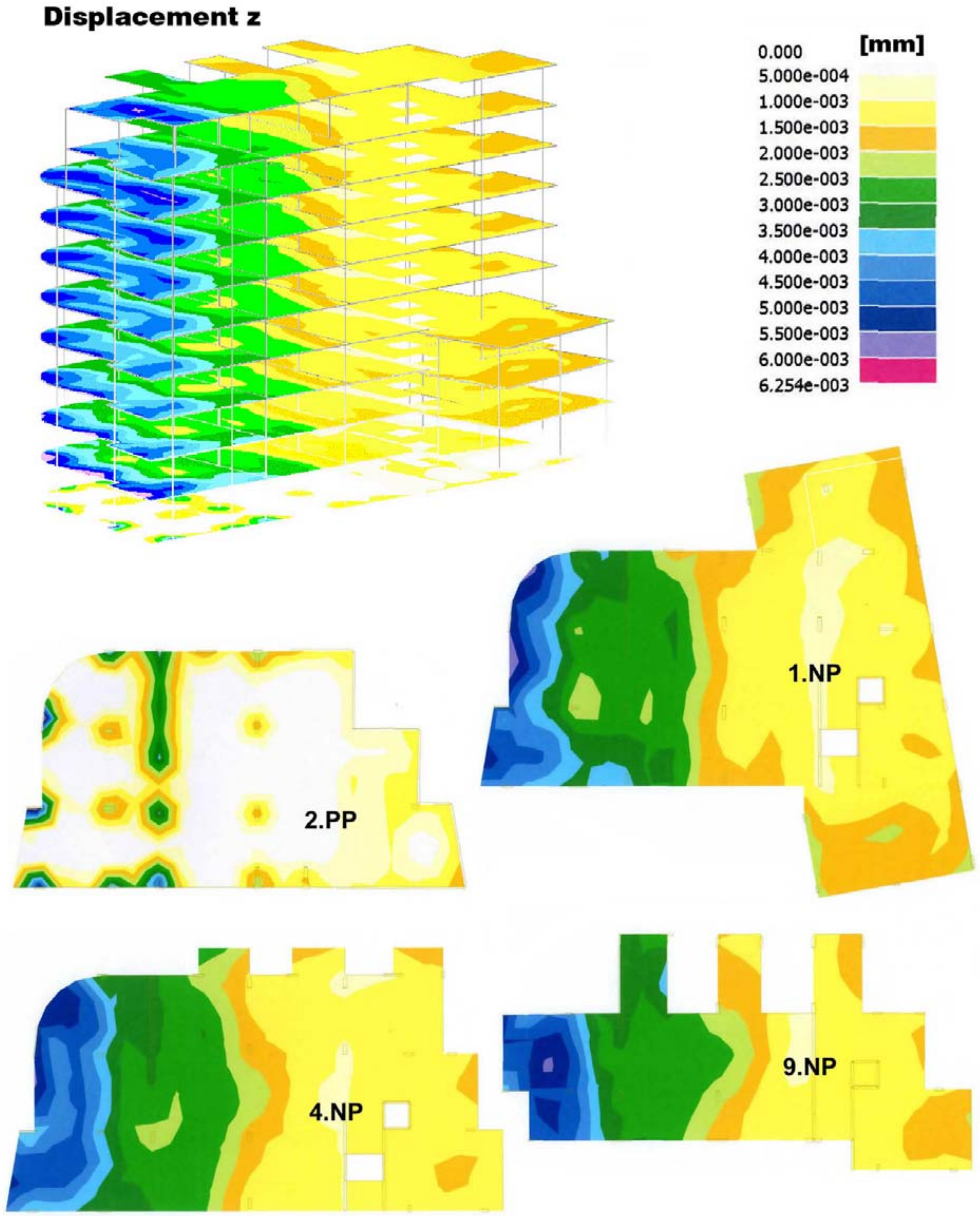

Figure 7: Maximum vertical displacements of selected storeys
(PP … under-ground and NP … above-ground storey).

Note: The excitation function is normalized; its maximum amplitude is equal to one, and the function is dimensionless. In the diagram its amplitude has been selected larger, in order to enable a comparison between the history of the excitation and the history of the response.

5 ASSESSMENT OF THE EFFECTIVENESS OF SPRINGING

An assessment of the effectiveness of the sprung system can be based on a comparison between the measured vibrations at the pile heads (Figure 3) and the vibration level of the individual storeys in the sprung building.

The measured dominant pile head frequencies corresponding to excitation by underground train traffic are within the frequency range of approx. 32 to 40 Hz (see Table 1). The frequency spectra have revealed that these dominant frequencies in the environs of 35 Hz correspond with the horizontal flexural pile vibrations (depending on the dimensions of the individual measured piles). Another significant frequency component ascertainable on the piles is the frequency around 10 Hz, obviously corresponding with the revolutions of the underground ventilation fans.

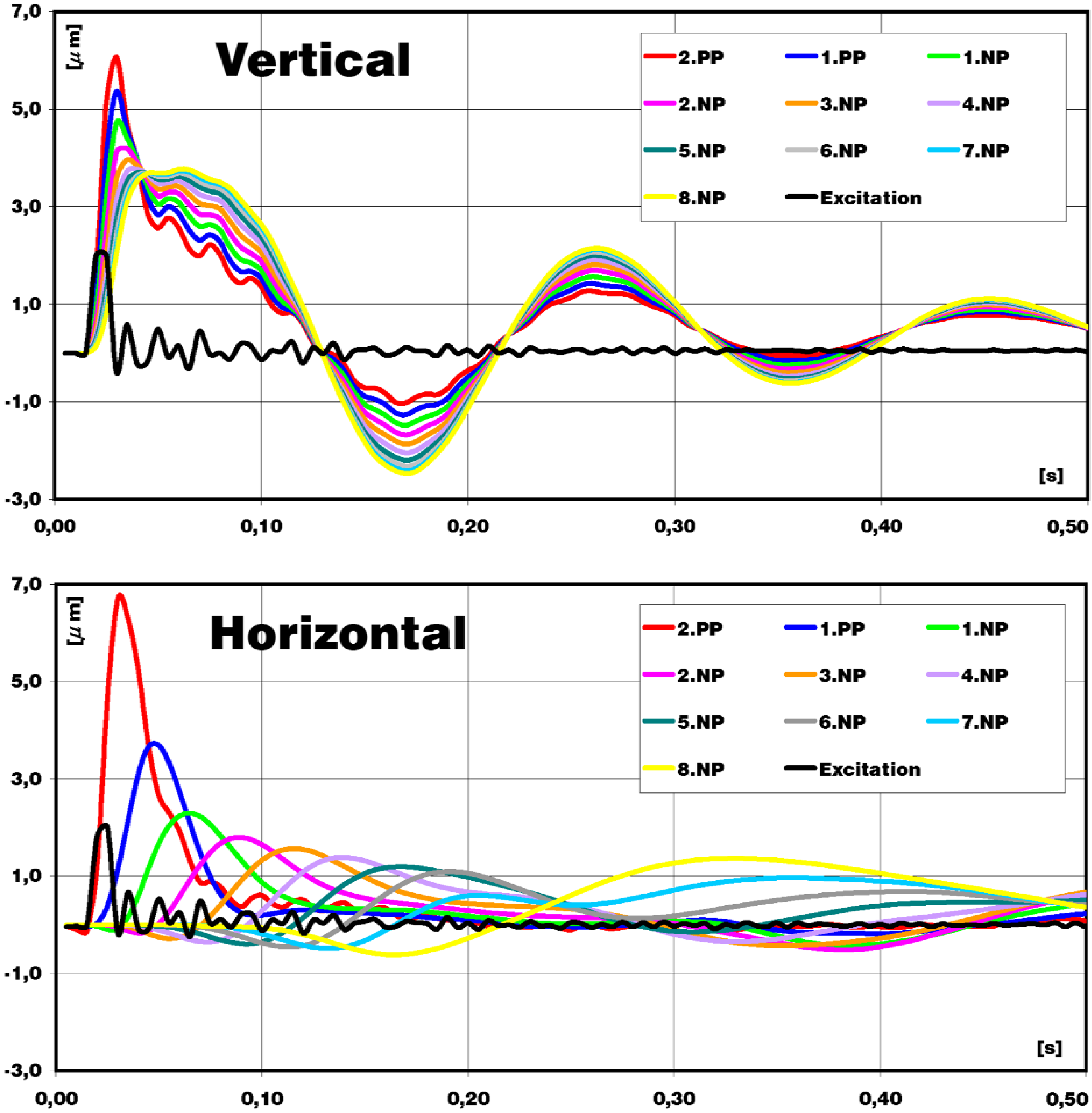

Figure 8: Prediction of vibrations at selected points (located on the structure side near the underground) in storeys as compared with the normalized excitation history in the vertical (up) and horizontal (bottom) direction.

Site	Acceleration a [mm/s^2]		Displacement y [μm]	
	Vertical	Horizontal	Vertical	Horizontal
Point 1	454 ~ 528	197 ~ 253	11.2 ~ 13.1	4.9 ~ 6.3
Point 2	490 ~ 690	212 ~ 359	12.1 ~ 17.1	5.2 ~ 8.9

Table 1: Measured acceleration intervals at pile head level and corresponding displacements y in the 31~40 Hz frequency range at the pile top

The measured dominant pile head frequencies corresponding to excitation by underground train traffic are within the frequency range of approx. 32 to 40 Hz (see Table 1). The frequency spectra have revealed that these dominant frequencies in the environs of 35 Hz correspond with the horizontal flexural pile vibrations (depending on the dimensions of the individual measured piles). Another significant frequency component ascertainable on the piles is the frequency around 10 Hz, obviously corresponding with the revolutions of the underground ventilation fans.

The low-frequency quasi-static vibration component ascertained on the piles just below 1 Hz attains acceleration amplitudes of the order of tens mm/s^2, and corresponds with the quasi-static horizontal displacements of the pile heads. This component poses a relatively low danger to the building, as its influence will be partly eliminated in the plan by a foundation slab of sufficient dimensions.

The springing of the building will shift its dominant vibrations into the range of the lowest natural frequencies of the translation vibrations or flexural vibrations of the building as a whole. In accordance with Figure 7 and Figure 8, the maximum level of the response of the sprung building lies in the peak deviations of up to approx. 7 μm.

For frequencies of up to 5 Hz, this value corresponds approximately to peak acceleration a_{peak}, or to effective acceleration a_{ef}:

$$a_{peak} \approx 0.007 \cdot (4\,\pi^2 \cdot 52) = 6.9 \text{ mm/s}^2 \quad (1)$$

$$a_{ef} \approx 0.707 \cdot a_{peak} = 4.9 \text{ mm/s}^2 \quad (2)$$

The above comparison shows that the influence of springing will manifest itself by the redistribution of dominant vibrations into the low frequency range of the springing and by the practically negligible amplitude range of the vibration level in the initially dominant excitation frequencies (Table 1).

6 CONCLUSION

The paper deals with the application of an elastic antivibration layer at the foundation base level in order to eliminate excessive vibrations propagating to the assessed building through the geological environment from an underground railway structure. When the train is in motion, the dominant vibrations are transferred to the environs in the form of non-stationary vibrations produced by the motion of the train across the interface of the different types of underground tunnel structures (in our case).

The measurements at the heads of selected foundation piles ascertained vibrations exceeding the permissible limit for human comfort. This was the main reason for springing the whole building structure. The histories of the measured vibrations were used as loads applied to a modelled building structure at the foundation base of which a separating elastic rubber layer had been designed. For such a model, the predicted vibrations in the individual storeys were shown and were compared with the level of excitation vibrations as the foundation base. In the case of hard inelastic placing of the building on piles without springing, the vibrations would propagate from the subgrade directly into the R.C. building structure, practically without decreasing. The applied springing, consequently, is a very efficient instrument for reducing the transfer of vibration from the subgrade to the interior parts of the building.

7 ACKNOWLEDGEMENT

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