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NUMERICAL STUDY OF BUILDING VIBRATION CAUSED BY TRAFFIC OF UNDERGROUND TRAINS

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Abstract. The paper focuses on numerical study how vibration due to underground trains influences the load-bearing building structures. Diagrams of vibration levels for monolithic floor slab depending on frequency are obtained. Levels of vibrations on floor slabs and columns are measured. The simulation of dynamic load from underground railway onto load-bearing building structures is presented as an example. Recommendations for generation of design model in dynamic analysis of structure are provided.

Keywords: natural vibrations, forced vibrations, vibration load, numerical simulation, computer simulation, finite element method, LIRA-SAPR.

Introduction

Thoroughfares including railway and underground lines are the main sources of vibration in buildings and structures located in urban areas.

Because of increase in cargo traffic of all types, increase in speed and intensity of traffic, it becomes necessary to obtain qualitative and quantitative evaluation as to how transport vibration impacts the structural safety of buildings. For some type of structures, especially old ones, located near thoroughfares, vibration caused by heavy vehicles, freight and / or underground trains may have an influence over strength and strain capacity of structures and produce crack propagation in load-bearing and external envelope structures. Protection of structures against vibration caused by underground trains has become highly critical in recent years when shallow tunnels are used for the new underground lines.

An important problem is to consider mutual influence of different building structures in the restrained urban conditions. An abundance of different objects of mutual influence causes significant man-made load on surface and underground structures as well as rock and soil bodies.

Mathematical simulation of the stress-strain state in such massives is the only tool that could provide qualitative and quantitative evaluation for behaviour of geomechanic system ‘soil body – elements of surface and underground structures’.

Review of publications

In Ukraine there are no regulations that stipulate allowable vibration in buildings and structures caused by transport vibration. The only document in this field is DSN 3.3.6.039-99 ‘State Sanitary Code for General and Local Vibration in Industry’. Regulations for vibration load for people inside buildings are stipulated in this document.

However, there are several international documents that stipulate frequency dependent criteria for vibration evaluation. Below you will find criteria (the most frequent in international practice) for vibration evaluation in structures; these criteria are stipulated by national codes and other normative documents of foreign countries:

In National Code of Germany DIN 4150-3:1999 ‘Structural vibration – Part 3’ ultimate values are stipulated for short-term vibration for extreme values of speed on foundation of buildings for three categories of buildings:

– business structures, industrial buildings and structures that have similar design (category 1);

– civil structures and structures that have similar design or purpose (category 2);

– structures that are not included into categories 1 or 2 and that have high social significance (for example, protected as historic monuments, category 3).

It is proposed to measure the speed V in horizontal direction for the upper floor slab of the building. Ultimate values of this parameter for the short-term or long-term vibration are presented in Table 1.

If ultimate values for floor slabs (walls) exceed the values mentioned in table 1, it is recommended to evaluate mechanical stresses.

Table 1. Recommended ultimate values of speed *V*

Category of building	*V*, mm/s	
	Short-term vibration	Long-term vibration
1	40	10
2	15	5
3	8	2,5

Note. Above-mentioned values may be applied to intermediate floor slabs of the building as well as to its walls.

In National Code of Great Britain B3 7635-2:1993 BS 7635-2:1993 'Evaluation and measurement for vibration in buildings – Part 2: Guide to damage levels from groundborne vibration' ultimate values (Fig. 1) are stipulated for short-term vibration for extreme values of speed on foundation of buildings for two categories of buildings:

– business and industrial buildings that have framework or reinforced concrete structures (category 1);

– civil and business structures that have light-weight design, design with no reinforcement or with light-weight framework (category 2).

It is supposed that moderate damage may take place if ultimate values are two times higher than the values mentioned in Fig. 1, and serious damage – if they are four times higher.

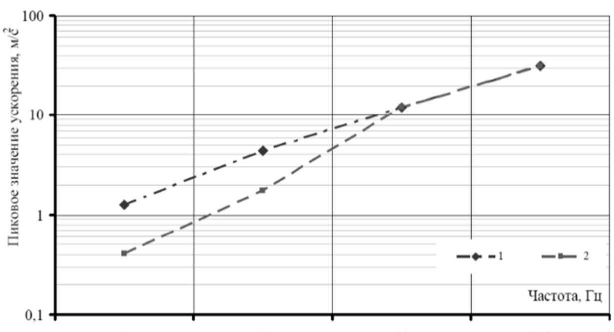

Fig. 1. Ultimate values of acceleration measured on foundation of a building

In case of low frequency signal that has significant components on frequencies low than 4 GHz, it is recommended to measure displacements. Ultimate extreme value of displacement for frequencies low than 4 GHz is equal to 0.6 mm.

In case of continuous vibration that could cause resonance of structure (especially in low frequencies), it is recommended to reduce ultimate values mentioned in Fig. 1 by half.

In National Code of Norway NS 6141.2001 ('NS 8141.2001 Vibralion and shock – Measurement of vibration vetocity and calculation of guideline limit values in order to avoid damage of constructions'), comprehensive criterion of evaluation is introduced for vibration caused by earthwork, demolition of structures and impact of traffic.

If the earthwork may cause vibration of structure at resonance frequency (for example, when vibration machines are used or in permanent or short intervals between start of electronic ignition system during explosion at construction work), then to evaluate whether arising vibrations are allowed, it is necessary to carry out additional research.

Ultimate value V for short-term vibration is determined for vertical component of extreme value of speed according to formula (1):

$$V = V_0 F_q F_b F_a F_k , \qquad (1)$$

where V_0 – default value of speed, equal to 20 mm/s; F_q – correction for the soil type at place where the structure is located; F_b – correction for type of structure; F_a – correction for distance between source of vibration and the place where it is measured; F_k – correction for type of vibration source.

Research on natural frequencies of vibrations in building structures is important as practical matter for solving different dynamic problems, including earthquake, vibration isolation and acoustics. Research on distribution of structure-generated noise and vibration in structure is a comprehensive engineering problem.

Agapov, Gorodetsky, Klovanich, Perelmuter, etc. conducted researches on simulation of building structures during dynamic loads, peculiar features of generation of design models (including with account of bedding), their evaluation and comparing analysed systems with real objects.

Main part

Engineering survey of structures of the office & shopping centre under construction at 7, B. Khmelnitskogo Str. was carried out in 2012 by specialists of State Research Institute of Building Production. The significant feature of site development is the underground station partially located in the underground part of the building (Fig. 2).

Defects were evaluated: crack propagation, chips, destruction of concrete cover, etc. in walls, floor slabs, foundations.

The survey of the office & shopping centre under construction at 7, B. Khmelnitskogo Str. was carried out (monolithic structures of basement, steel structures of framework, walls, floor slabs).

Unfinished building structure by structural elements that should be erected according to is considered as specific permanent structure (I group of importance) with normative lifetime of 175 years.

Fig. 2. The building under consideration and location of metro tunnel

The work schedule composed according to, included:

– examination of technical state of erected monolithic structures of the building framework with photo-fixation of existing defects and damages;

– instrumental examination of concrete strength;

– evaluation of obtained data and providing conclusions and recommendations;

– evaluation of impact of long-time vibrations of the underground railway on the foundation slab and load-bearing structures of the building.

Purpose of the work is to determine technical state of the framework structures of the building in order to continue construction works.

Instrumental verification of geometrical parameters of the building at 7, B. Khmelnitskogo Str. for columns, walls, floor, ceiling, lift shaft is carried out in order to find out vertical and horizontal displacements of erected structures from design location. Instrumental verification is carried out according to regulations of valid building codes and standards.

Obtained results demonstrates that defined precision was observed when new structural elements of the building (7, B. Khmelnitskogo Str.) were erected.

To determine numerical values of vibration with the help of vibrometer, measurements were taken with three vibrator inverters in the mode of automatic registration of mean-square and max levels of vibration acceleration with the averaging time of 1.5 and 10 s.

According to, technical state of the framework structures is considered as unserviceable (state III). Concrete strength in RC monolithic structures was determined by nondestructive sclerometric method.

Measurement results of concrete strength in monolithic RC walls and floor slabs were applied to computational investigation in order to define real stiffness parameters for structural elements.

Destruction of foundations and underground walls is 15–20% and in some places 50–80%, which is much higher than in similar buildings located inside blocks.

It is mainly related to low-damped settlements on soft water-saturated soil in permanent action of considerable vibrations caused by underground railway.

Reaction of building and its elements depends not only on level and spectral content of vibrations transferred by the soil but on dynamic parameters of load-bearing and enveloping structures. This concerns mainly frequencies of natural horizontal vibrations of buildings and vertical vibrations of elements of floor slabs, soil type, etc.

Envelope line of narrow spectrum of vibration acceleration in floor slab is the solid line in direction of three orthogonal axes. Envelope line is obtained by results of multiple measurements of vibration (not less than 3 hours at every point, traffic interval for trains ~5 min.) and it is presented in Fig. 3.

Levels of vibration acceleration L_a in figures are presented in dB:

$$L_a = 20log_{10}\left(\frac{a}{1\cdot 10^{-6}}\right), \quad (2)$$

where $1\cdot10^{-6}$ – default level of vibration acceleration a, m/s^2.

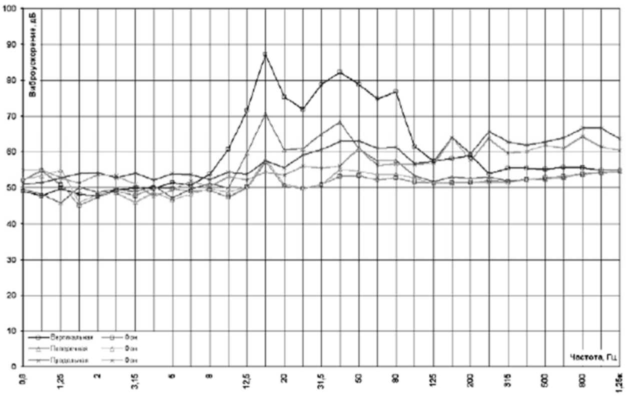

Fig. 3. Spectogram of max levels of vibration in floor slab

Traffic analysis of underground trains shows that as number of passengers is increased (rush hour between 17 and 19 hours), the levels of vibration acceleration are 3...3.5 dB higher relative to the time from 19 to 22 hours. Levels of vibration acceleration also depend on technical state of rail track and railway vehicles, train speed (in rush hour speed is higher). All above-mentioned factors also influence the frequency distribution of level of vibration acceleration.

Obtained data indicates that max levels of vibration acceleration for floor slab are obtained for vertical vibration within the frequency range from 16 to 80 Hz and exceed values along other directions by more than 15 dB (more than 6 times higher).

Modal analysis of the system ‘soil body – elements of surface and underground structures’ based on FEM

Analyses of stress-strain state of the system ‘soil body – elements of surface and underground structures’ are carried out by finite element method.

Mutual interaction of bedding and the surface part of building presented in Fig. 4 (dimensions in plan 18.0×51.6 m, height about 18 m) is considered. The building consists of two volumes of different height; this causes different loads at certain zones of bedding.

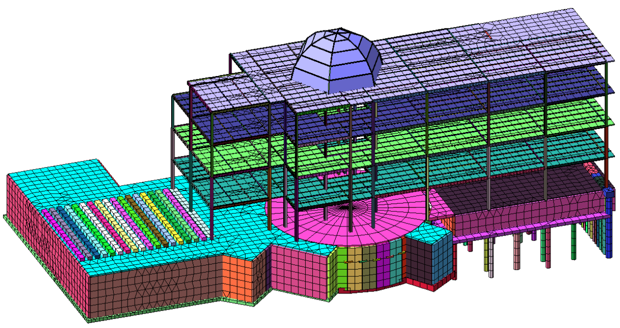

Fig. 4. FE model of office & shopping centre at 7, B. Khmelnitskogo Str. in Kiev

To determine stress-strain state of the building with account of pulse processing during pulse transition from the soil to foundation of building, the structure and soil body were simulated with the finite element method. 3D soil body is simulated in the SOIL module according to data from engineering-geological survey (see Fig. 5).

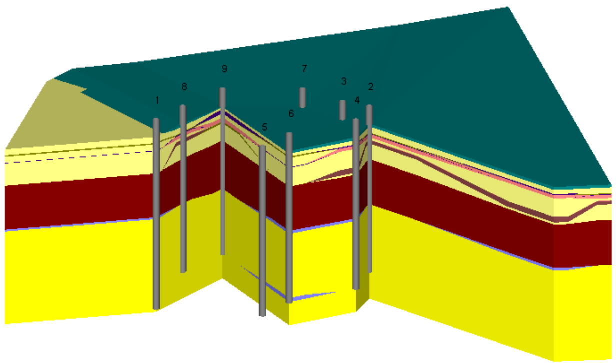

Fig. 5. Fragment of 3D soil model according to data from engineering-geological survey

Such method of generation for system 'soil body – elements of surface and underground structures' represents quite a promising solution in terms of forecasting behaviour of buildings and structures when permanent dynamic loads are transferred through the soil.

Time period for which dynamic loads were determined is taken as equal to 10 seconds. Parameters of vertical and horizontal vibrations at check points (where in-situ measurements were made) were obtained in analysis.

FEM equation for natural vibrations (3):

$$[M]\{\ddot{u}\}+[K]\{u\}=\{0\}, \tag{3}$$

where $[M]$, $[K]$ – stiffness matrix and mass matrix respectively, $\{u_i\}$ – column vector of displacements. This equation was solved with the help of LIRA-SAPR software. Natural frequencies of vibrations thus obtained are compared to experimental data and presented in Table 2.

Table 2. Comparison: experimental data and design data computed by FEM

Experimental data	16.3	24.2	35.4	42.5	57.9	71.3
Modal analysis	17.9	26.6	35.8	42.3	56.9	75.9

It is important to note that obtained results differ by more than 10% for the lowest frequency 16.25 Hz where the highest levels of vibration are found during train movement.

Conclusions

1. Study of vibration (caused by underground trains) levels of monolithic floor slab shows that vibration levels are dramatically modified when different trains pass. The highest levels of vibration acceleration for the floor slab are obtained for vertical vibration for the frequency range from 16 to 80 Hz and exceed values along other directions by more than 15 dB (more than 6 times higher).

2. Measured values of vibration of certain floor slabs in the building under consideration significantly (up to 2 times) exceed allowed values by vertical logarithmic level of vibration acceleration in strips with mean geometric frequencies 31.5 and 63 Hz.

3. Results of experimental and numerical analyses of monolithic floor slab differ by more than 10% for the lowest frequency 16.25 Hz where the highest levels of vibration are obtained when underground trains pass.

4. Parameters for fragment of floor slab are identified based on measured properties of its vibration. The following concrete moduli of elasticity were found: for slab E_n = 30.24 GPa (reducing design model by 6%), for column $E_к$ = 33.67 GPa (increasing design module by 18%) for floor slab at point where floor slab and column are connected $E_{пк}$ = 191.1 GPa (increasing design module by 5.97 times). Results obtained based upon this enable you to improve the accuracy of predictions for vibration parameters for the wide range of dynamic, earthquake and vibro ecology problems.

5. To carry out dynamic analyses for vibration distribution along building structures of framed building, it is recommended to use experimental data together with identification results.

In conclusion, it should be noted that study as to how vehicle vibration influences the bedding, buildings and structures is an important and urgent issue. The above-mentioned examples show that correct evaluation and account of vibration influence may help you avoid different undesirable situations and generate high economic returns when developing urban areas near highways with intensive road traffic.

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