Stress-strain state of the structure in the service area of underground railway

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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 with account of load transmission through the soil. Recommendations for generation of design model in dynamic analysis of structure are provided.

1. Introduction
In recent years, many scientists have come very close to developing adequate static-dynamic design models for account of the interaction of buildings and structures with soil under dynamic loads [1–4]. Using such models to study the stress-strain state of building structures throughout their life cycle is of particular interest. Such models include both buildings designed and built in the metro area and buildings that have been deformed in the course of long-term operation and subject to new dynamic loads transferred to buildings through the soil. Practically across the whole area of Ukraine there is a high density of residential development in large cities, the complexity of engineering and geological conditions, as well as the long life cycle for most buildings. That’s why, the issue of how main load-bearing structures of buildings take considerable loads and actions (that arise from the nearby thoroughfares, mainline railroads and underground railway) has come to the fore.

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.

Numerical simulation of the stress-strain state in such structures is the only tool that could provide qualitative and quantitative evaluation for behaviour of geomechanic system “soil body – elements of surface and underground structures” [5].

For that matter, numerical study of structures of the office & shopping centre under construction at 7, B. Khmelnitskogo Str. was carried out. The purpose of this work was to determine adequacy of the static-dynamic design model used in dynamic loads transferred through the soil stratum.
2. Theory

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. 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).

In National Code of Great Britain В3 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 (figure 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 figure 1, and serious damage – if they are four times higher.

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

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

![Figure 1](image-url)

**Figure 1.** Ultimate values of acceleration measured on foundation of a building.

In National Code of Norway NS 6141.2001 (‘NS 8141.2001 Vibration and shock - Measurement of vibration velocity 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.
V. Agapov, V. Banakh, A. Gorodetsky, S. Klovanich, Y. Nemchinov, N. Marjenkov 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.

3. Methods
Engineering survey of structures of the unfinished office & shopping centre under construction at 7, B. Khmelnitskogo Str. was carried out. Monolithic structures of basement, steel structures of the framework, walls and floor slabs were examined. Defects were evaluated: crack propagation, chips, destruction of concrete cover, etc. in walls, floor slabs, foundations (figure 2).

Unfinished building structure by structural elements that should be erected according to [9] is considered as specific permanent structure (I group of importance) with normative lifetime of 175 years.

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.

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 [9], 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. [7,9,11,12].

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 figure 3.

Levels of vibration acceleration \( L_a \) in figures are presented in dB [0]:

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

where \( 1 \cdot 10^{-6} \) - default level of vibration acceleration \( a \), m/s².

Figure 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.

The main source of vibration is the impact when the wheel of the train passes through the rail joint. The resulting vibration of the tunnel lining reduces up to the time when the next wheel passes the rail joint.

In addition, there is a polyfrequency vibration from the imperfectly smooth surface of the wheel and rail material, from the deformed wheels as well as from the effect of the ‘wheel wobble’ in trains during motion. Of the loads mentioned above, vibration load in the frequency range of 25-50 Hz prevails. If this frequency of vibrations is close to the natural frequency of the tunnel lining, even with account of the filtering features of the soil, the very structure of the path, regardless of the fact wether the path is vibrated or not, the wave radiation can be increased [2,3]. Therefore, with regard to metro, in general, one can not speak of one prevailing frequency. Thus, rather than going into design features of the lining and the upper structure of the track, we could take the operating frequency range of vibration from the metro 20-70 Hz. A typical feature of this range is that natural frequencies of the floor slabs in buildings usually fall within this range [2-4]. It can be seen from obtained data (figure 3). The highest levels of vibration acceleration of the floor slab are obtained in vertical vibration for the frequency range from 16 to 80 Hz and exceed values in other directions by more than 15 dB (more than 6 times).
For comparison, the intensity of soil vibrations near the metro corresponds to 6, 7 units of magnitude. The map at the Institute of Geophysics shows that an earthquake of magnitude 5 - in most parts of Ukraine occurs every 100 years. Earthquake of magnitude 6 units - every 5 thousand, that is, the probability of an earthquake in the zone of Kiev and the Kiev region is quite small. In this case, the permanent vibration from a moving vehicle (but with relatively small amplitude of vibrations) may cause damage of the load-bearing structures, crack propagation and, if measures are not taken, even to destruction.

The problem under consideration has the following main tasks:
- to study the soil dynamics and vibration of protected structures from various types of dynamic loads;
- to estimate the risk level as to whether parameters of the stress-strain state in load-bearing structures of nearby buildings may estimate the normative values;
- to develop design methodology for similar buildings.

Thus, there are principal lines in this paper:
1. To develop methodology for analysis and design of a building in external vibration caused by the underground rolling stock. The work is carried out using LIRA-SAPR program based on FEM. This program enables the user to analyse buildings of all types in order to evaluate and then forecast behaviour of structure.
2. To develop methods for preliminary assessment and evaluation of dynamic phenomena in high-rise buildings at the stages of design, construction and maintenance in order to prevent negative effects on structural elements and people from vibrations caused by the underground train.

4. Mathematical relations
Vertical and horizontal components of vibration velocity at the soil surface are determined by formula:

\[ v_{1,2}(i) = \sqrt{v_R^2 + v_{1,2}^2} \]

where \( v_R \) – vibration velocity caused by Rayleigh wave and calculated by formula

\[ v_R = \frac{R_0}{H_0} v_{\text{max}} \exp(-\beta \cdot k_R \cdot x) \]

\( \beta \) – damping ratio in soil;
\( k_R \) – wavenumber of Rayleigh wave;
\( v_{1,2} \) – appropriate projections of vibration velocity caused by longitudinal wave in soil and calculated by formula

\[ v_{1,2} = \sqrt{\frac{R_0}{x^2 + H_0} \left( v_{\text{max}}^2 + v_{\text{max}}^2 \exp(-\beta \cdot k_R \cdot x^2 + H_0^2) \right)} \]

In this case \( H_0 \) – depth at which the trough part of the tunnel lining is located;
\( x \) – distance from longitudinal axis of the tunnel;
\( R_0 \) – characteristic dimension that represents min from \( D/2 \) – half width of the tunnel;
\( k_R = \frac{c_1}{\omega} \) – ratio of velocity of longitudinal waves in soil to angular frequency;
\( v_{1,2,\text{max}} \) – max values for vibration velocity at the trough part of the tunnel lining;
\( v_{\text{max}} \) – max from the above.

The values of the lowest-frequency components of transport dynamic loads are often close to the values of natural frequencies of vibrations in most buildings. As natural frequencies are often within 2-8 Hz, it may cause additional sagging of buildings by 50-150 mm [5,8].
5. Results and discussion

Modal analyses of stress-strain state of the system ‘soil body – elements of surface and underground structures’ are carried in LIRA-SAPR program based on FEM.

Mutual interaction of bedding and the surface part of building presented in figure 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.

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 in the LIRA-SAPR program.

To transfer dynamic loads through the soil to the load-bearing structures, it is possible to perform computer simulation in several ways. In this paper it is proposed to simulate the soil with solid finite elements. This simulation type provides min error in transmission of parameters of dynamic loads in comparison to results of measurements. The subway tunnel with reinforced concrete sheeting is simulated with plate FEs. Dynamic loads are applied at the place of their origin, that is, in the tunnel.

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

The plan view of the structure and diagonal location of underground railway tunnel are presented in figure 5.

3D soil body is simulated in the SOIL module according to data from engineering-geological survey (see figure 5).
Figure 5. Model of the structure with soil and tunnel located along the underground railway.

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.

Natural frequencies of vibrations thus obtained are compared to experimental data and presented in Table 1.

Table 1. Comparison: experimental data and design data computed by FEM.

| Experimental data | 16.25 | 24.17 | 35.42 | 42.5 | 57.92 | 71.25 |
|-------------------|-------|-------|-------|------|-------|-------|
| Modal analysis    | 17.9  | 26.55 | 35.75 | 42.31| 56.97 | 75.95 |

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.

6. Conclusions

1. Buildings and structures that will be erected within the area of transport vibration should be designed with account of damping properties of soil and bedding. The soil should correspond to design loads of vehicles.

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 $E_c=33.67 \, GPa$ (increasing design module by 18 %) for floor slab at point where floor slab and column are connected $E_{nc}=191.1 \, GPa$ (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.

Acknowledgements
The research leading to these results has received the funding from Latvia state research program under grant agreement "INNOVATIVE MATERIALS AND SMART TECHNOLOGIES FOR ENVIRONMENTAL SAFETY, IMATEH”.

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