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The impact of vibration on buildings: problems and solutions

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Abstract. The article presents a comprehensive overview of a study investigating the influence of soil-foundation interaction on the natural frequencies and vibration safety of reinforced concrete cellular and frame buildings. Through numerical modelling and analysis, the researchers investigate the relationship between structural modes and soil-induced vibrations, emphasizing the sensitivity of vibration frequencies to soil composition. Findings reveal that alterations in foundation conditions can significantly affect building dynamics, particularly in mid-rise structures, highlighting the importance of targeted monitoring for early detection of potential issues. Furthermore, the study discusses the implications of vibrations on human comfort and safety, underscoring the need for effective vibration mitigation strategies. Various damping systems, including hydraulic, dry friction, and dynamic dampers, are proposed as practical solutions to minimize the adverse effects of vibrations on both structures and occupants. Overall, the study underscores the critical role of vibration safety in ensuring the resilience and well-being of buildings and their inhabitants.

1 Statement of the problem

Due to the increasing volume of construction in areas exposed to vibrations of various kinds, the problem of controlling these vibrations is becoming increasingly important. Their constant impact on structures causes not only material damage, but can also negatively affect the health of people in these premises [1]. Vibrations in a building can not only cause unacceptably high levels of displacement, but also lead to an increase in airborne noise. The impact criteria for regulating the maximum permissible levels of vibrations of building structures are established by the State Building Standards (DBN B.1.2-10:2021 “Protection against Noise and Vibration”) [2]. It has been determined that the amplitudes of vibrations are limited in the frequency range of 1.4-88 Hz, which indicates the importance of taking these parameters into account when designing and operating buildings. Thus, ensuring the safety and comfort of citizens' life and work, understanding and effective management of vibration in buildings is becoming an extremely important task.

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The aim of the work is to study the effects of vibration on the human body and aspects of vibration safety in buildings, to consider strategies for preventing and minimizing the effects of vibration on residential buildings.

2 Main part

Vibration is considered to be one of the types of physical environmental pollution that can lead to a deterioration in the living conditions of building residents. The construction of modern residential complexes in areas affected by highways, railways and trams or near highways with heavy truck traffic may lead to violations of construction and sanitary standards and regulations regarding the safety of structures and protection against vibration and noise impacts in the premises. Vibration impacts can have negative consequences for the condition of the building, namely, lead to visible damage to structures and reduce their service life [1].

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Transport vibration can be a factor in causing discomfort and negative impact on human health and well-being. Long-term vibration impact can lead to irreversible changes in internal organs and general health. On the other hand, it is well known that people tolerate much higher vibration levels in vehicles than in buildings. This is due to the fact that vibrations in these two cases are in different frequency ranges [3]. The frequencies of vibration perception in buildings are in the low-frequency range, close to the frequencies of the internal organs of the human body. Prolonged periods of exposure to low-frequency vibrations may have a negative impact on health, the functional state of the central nervous system and cardiovascular activity, and may increase the risk of developing certain diseases [1]. In addition to transport vibrations in the premises, vibrations caused by the operation of elevators and construction work near residential buildings, such as pile driving or dismantling of building structures, can occur. A particular problem is the construction of subways in large cities, where lines run under existing residential areas, as the zone of vibration transmission from the subway to the houses is within a radius of up to 40-70 m from the tunnel [1].

In the context of human perception of vibrations, two types should be distinguished: active and passive vibration perception [3]. Active vibration perception is the case in which a person is aware of or feels the vibration of the environment, such as when a person feels the vibration of a car while traveling. Passive vibration perception is a case where a person is not aware of the vibration, but their body is still exposed to vibration, such as being indoors where the source of vibration is outside the room, such as traffic passing on the street or equipment operating in the neighboring area. It is important to be able to identify and take into account both of these types of perceptions when designing buildings to ensure a comfortable environment for people. In cases where vibrations in buildings are felt by their occupants, their quality of life or work efficiency may potentially be affected [4]. In particular, in practice, it has been found that people usually feel more perceptible vibrations in vehicles than in buildings. This is due to the fact that vibrations in these two cases are in different frequency ranges. The frequencies of vibration perception in buildings are in the low-frequency range, close to the frequencies of the internal organs of the human body [1].

That is why active and passive perception should be considered separately. Building vibration can be felt by human inhabitants at levels much lower than those that can cause damage to the building. The level of vibration that affects human comfort is lower than that associated with building damage. Therefore, today, the dominant design and diagnostic parameter in the context of vibration is its perception by humans [3].

In most cases, the vibration generated by various sources has a complex spectrum of frequencies but is characterized by a different distribution of intensity across frequencies and a different pattern of change in total vibration energy over time. A person can feel vibration from fractions of a hertz to 800 Hz, and high-frequency vibration is perceived similarly to ultrasonic vibrations, which cause a thermal sensation.

Mechanical vibrations that affect a person are perceived by his or her body as an oscillatory system in which biomechanical reactions occur. Particular attention is paid to the resonance phenomenon that occurs both in the whole body and in individual organs and systems. Studies have shown that at a vibration frequency of more than 2 Hz, a person is perceived as a solid mass, and for a sitting person, the body resonance falls within the interval from 4 to 6 Hz. The other band of resonant frequencies is in the range of 17-30 Hz and affects the head-neck-shoulders system, where head vibrations can be three times stronger than shoulder vibrations. At high vibration levels in the range of 4-10 Hz, a person may feel pain and discomfort due to resonant vibrations of the "chest-abdomen" system. When the frequency range of 8-27 Hz is reached, head resonances can affect reduced visual acuity due to the displacement of the object image relative to the retina. Exceeding the limit values of the root mean square of vibration accelerations a_z can cause a noticeable deterioration in visual acuity. A graph of the dependence of the rms values of vibration accelerations a_z on frequency is shown in Figure 1. Thus, the human body is a complex oscillatory system with its own resonance, which determines the frequency dependence of many biological effects of vibration [1].

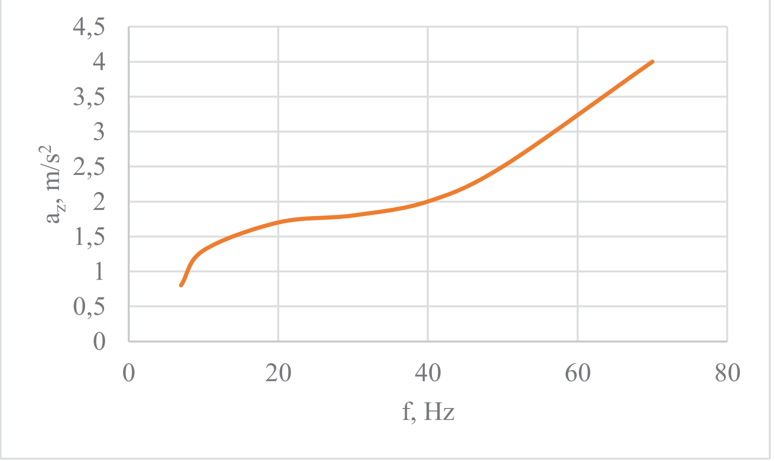

Fig. 1. Root mean square values of vibration accelerations a_z

Dynamic impacts on buildings and structures belong to the category of impacts that are most difficult to take into account when calculating construction objects at the stages of design, construction, operation and reconstruction. This is due to the specifics of the dynamic response of buildings to external dynamic effects, which depends on the design features of the object, the type of dynamic effects, the way they are taken into account when performing dynamic calculations, the design models adopted and the calculation methods used [1].

A feature of the operation of buildings and structures in complex engineering and geological conditions is that, as a result of deformations of the foundation, they receive uneven settlements, which cause changes in the height position of the supporting structures, their roll, uneven settlements of the supporting areas, the presence of defects in the form of cracks, spalls, exposed working reinforcement, etc. [3].

In these cases, the nature of the work and the reaction of the supporting structures and the structure as a whole to the static operating load change. In the same case, if the structure is under the influence of dynamic loads of even low intensity, the behaviour of the structures can change significantly.

The next important factor is the characterization of the parameters of the environment through which dynamic actions are transmitted to the building. Obviously, in the process of transmitting dynamic actions of different nature, the adequacy of the overall model and the correctness of the calculation depend on the model of the soil foundation or the method of its consideration.

Scientists F.M. Dimentberg, L.D. Isaev, Y.G. Panovko, D.V. Frolov, M.I. Kazakevych, V.V. Kulyabko studied in their works the problems related to ensuring the comfort of people in buildings and structures during their construction, operation and reconstruction. In particular, these researchers considered the issues of vibroecology, monitoring and vibro-diagnostics [4].

Changes in the stiffness, dissipative and inertial characteristics of building structures and their foundations under unfavourable operating conditions result in changes in the dynamic response of building objects. This necessitates the development of methods that can correctly and accurately determine, by calculation or direct measurement, analyse and predict, and change these properties [4].

Diagnostics and forecasting of the dynamic response of structures are becoming increasingly important when performing work related to reconstruction, conservation or deconservation, modernization or repurposing of construction facilities. In such cases, changes in the operating conditions of structures, their foundations and foundations, external, especially technological, static and dynamic loads, as well as the properties of individual structural elements of buildings and structures may undergo significant changes [4].

In modern cities, there is a significant number of old housing stock buildings alongside newly constructed buildings. Thus, there are many studies devoted to the determination of vibration characteristics using modal analysis methods for old buildings as well as new buildings. The main purpose of all studies is to investigate the impact of vibrations of different nature on the structural elements of buildings and improve living conditions. For example, the study [5] assesses the impact of vibrations on medium-rise cellular buildings. In order to investigate the effect of vibration frequency and structural changes on the natural frequency of three different types of nine-story buildings, finite element models of the following types were developed. The height of the buildings was 26.11 m, and the plan dimensions were 11.620×33.84 m. The material constants were assumed: elastic modulus of 2490 kN/cm^2, shear modulus of 1037.50 kN/cm^2, Poisson's ratio of 0.2, and specific gravity of 25 kN/m^3. For the walls with aggregate, the material constants were as follows: elastic modulus 1800 kN/cm^2, shear modulus 750 kN/cm^2, Poisson's ratio 0.2, and specific gravity 17.50 kN/m^3 [5].

The masonry infill was appropriately included in the finite element model. The joints of the plate elements of the cellular prefabricated building were modelled as a hinged joint of two surfaces. For buildings, a fixed base model was considered. The natural frequencies of the models were calculated using the iterative Lanczos method, which is suitable for large models [5].

The study [6] examined the changes in the natural frequencies of a reinforced concrete frame building when interacting with different types of soil foundations. The structural scheme of the building was assumed to be a frame one, where the spatial stiffness is provided by rigidly fastening the crossbars to the columns and by two stiffness cores connected to the elevator shafts. The building's foundation is slab. The dimensions of the building in plan are 18×58 m, floor height is 4.2 m, the number of floors is 5 and 1 basement. The construction area is Dnipro, Ukraine [6].

Three design schemes were developed for analysis. The first assumes that the structural elements of the building are made of heavy concrete C25 without considering the soil base, while the second incorporates the soil base. The third variant incorporates fibre concrete properties for the floor slabs and beams, and also considers the soil base [6].

In the study by [5], the fundamental frequency f_1 is approximated by the structural frequency of the fixed-base model f_s and the rocking frequency f_r. Typical fundamental frequencies obtained experimentally are given in Table 1 and Figure 2 [7].

Table 1. Fundamental frequency ranges of buildings [7].

Number of Stories (Number of Assessed Buildings)	Typical Fundamental Frequency Range, Hz	Mean (Standard Deviation), Hz
1–3 (63)	1.2–12.5 6.1 (2.8)	6.1 (2.8)
4–5 (108)	0.7–6.5 3.8 (1.2)	3.8 (1.2)
6–7 (91)	0.8–4.8 2.8 (0.8)	2.8 (0.8)
8–9 (71)	0.7–3.3 2.1 (0.6)	2.1 (0.6)
10–12 (86)	0.7–3.5 1.9 (0.6)	1.9 (0.6)
13–16 (53)	0.4–2.2 1.3 (0.4)	1.3 (0.4)

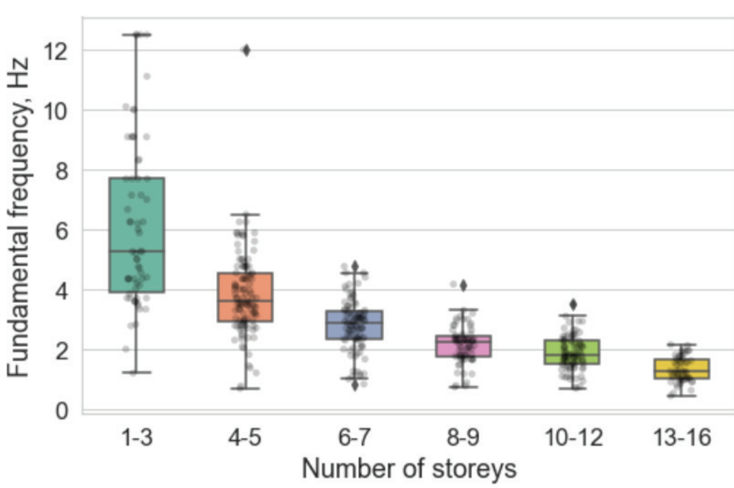

Fig. 2. Graph of the ranges of the main frequencies of buildings [7]

Table 2 summarizes the results derived through finite element computations, which separately decomposed the contribution of each modal component for the three vibration modes (Fig. 3) for cellular structure, reinforced concrete (RC) building.

Table 2. Structural frequencies and their modal components for cellular structure building.

Type of Soil	Para-Meter	Mode # of cellular structure, reinforced concrete (RC) building		
		Lateral	**Longitudinal**	**Torsional**
I	f_1	1.255	1.973	2.171
	f_s	5.339	6.800	7.481
	f_r	1.291	2.062	2.269
	f_s/f_1	4.25	3.45	3.45
II	f_1	0.867	1.628	2.164
	f_s	5.339	6.800	7.481
	f_r	0.879	1.677	2.261
	f_s/f_1	6.16	4.18	3.46
III	f_1	1.025	1.796	2.166
	f_s	5.339	6.800	7.481
	f_r	1.044	1.862	2.263
	f_s/f_1	5.21	3.79	3.45

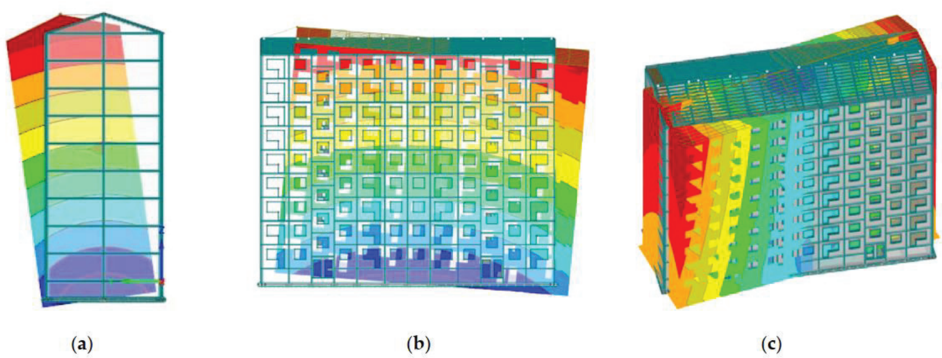

Fig. 3. Vibration modes in each direction: a) lateral mode; b) longitudinal mode; c) torsional mode obtained from the study [5]

This analysis revealed the correlation between the structural mode and the mode influenced by Soil-Structure Interaction (SSI) effects [5]. The correlation between f_s/f_1 underscores the role of vibration frequency in determining the lowest natural frequency, a value that escalates with the building's stiffness on weaker soils. Across all cases examined, f_r remained below f_s, implying that the minimum possible ratio value was 1.43 [5].

A lower value indicates a higher sensitivity of the fundamental frequency to potential damage to the building. The largest values of the f_s/f_1 ratio was observed for vibration modes aligned with the narrower width of the building, underscoring the necessity of focused monitoring of soil parameters with respect to the natural frequency of this vibration mode. However, when monitoring is performed for the structure itself, it's crucial to consider torsional and lateral modes in alignment with the greater stiffness of the building [5].

The study [5] discovered that soil type significantly influences vibration frequencies, particularly affecting the first vibration mode in the narrow direction of the building. In rigid structures, alterations in soil composition have minimal to no impact on torsional vibration components. Vibration frequency emerges as a highly sensitive parameter for medium-height buildings during foundation condition monitoring. Changes in this parameter can promptly indicate potential issues such as building damage due to uneven settlement, leading to cracks or undesired displacements of horizontal elements. Hence, the study has unveiled the vulnerability of vibration frequency to foundation changes in mid-rise buildings, particularly those with a cellular structure.

Based on the results of the numerical modelling in the study related to multi-storey frame buildings [6], the oscillation forms were obtained (Fig. 4) and graphs were constructed for each of the variants of the design scheme (Fig. 5,6). As a result, it was found that the eigenvalues of the first mode of natural oscillations are the largest and notably distinct from the others. The second and third modes exhibit closely similar values, while the remaining modes are nearly equal to each other with insignificant differences. The frequencies of the natural waveforms are lowest for the first mode, increasing with the order of the mode. Frequencies of the second and third modes, as well as the fourth and fifth modes, are similar. The frequencies of other natural oscillation modes are nearly identical [6].

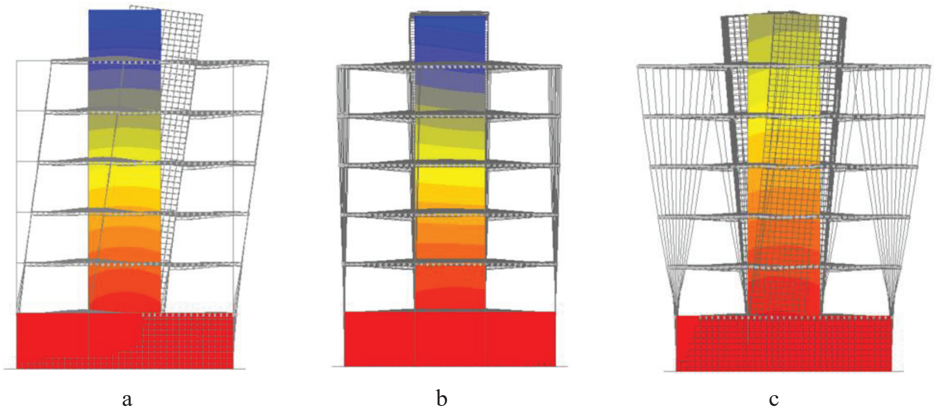

Fig. 4. The forms of oscillation: a - first mode; b - second mode; c - third mode

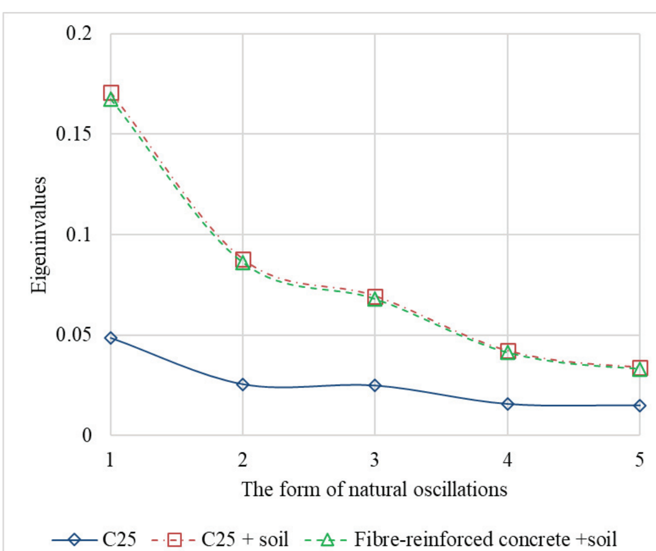

Fig. 5. Graph of eigenvalues of natural oscillation forms

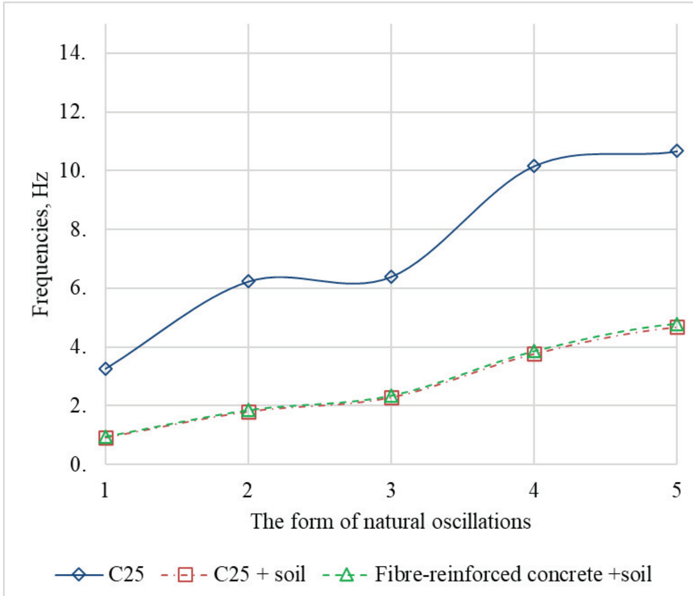

Fig. 6. Graph of frequencies of natural oscillation forms

An effective measure for the dynamic protection of buildings to minimize the impact of vibrations on the state of structures and human health is the installation of inertial vibration dampers, seismic isolation, and various types of dampers [4]. The latter can be divided into two main categories: hydraulic and mechanical. In hydraulic dampers, energy is dissipated due to the resistance arising from the movement of a pressurized fluid. These dampers absorb energy well, gradually coming into operation, and do not create high-frequency vibrations. However, they are considered relatively expensive and require maintenance during their operation [5]. In recent years, dry friction dampers (DFDs) have become widely used in practice. Their advantages are simplicity and reliability of design; no need for maintenance during operation; reusability; low cost and ease of installation. These devices are also characterized by high dissipative properties that allow them to effectively absorb energy during earthquakes and other dynamic loads of various nature [4]. In the event of seismic vibrations, the upper part of the dry friction dampers shifts relative to the lower part, and friction forces absorb the energy of seismic vibrations [5].

With dynamic or shock dampers, the energy of the vibrations is transferred to the damper, which oscillates with increased amplitude, and is used to damp vibrations in tall industrial buildings, towers, and building elements. These dampers can be made in the form of an additional mass that is attached to the structure or directly to the machine that generates the vibrations. Dampers are also widely used, the mass of which moves along a curved surface or is suspended like a pendulum. These dampers use various elastic elements, such as steel springs, rubber elements, and materials with increased dissipative properties, such as rubber or plastics. This reduces the number of stress cycles, which has a positive effect on the durability and reliability of structures [5].

3 Conclusion

As a result of a comprehensive study of structural dynamics and soil-foundation interaction, critical aspects of vibration safety and its impact on human well-being have been identified. The study emphasizes that changes in the condition of the foundation, especially in mid-rise buildings, can significantly affect the frequency of vibrations, which can potentially lead to structural damage or discomfort for occupants.

Vibration frequency, especially in the first mode of vibration, has been identified as a sensitive indicator of building health, and changes in it point to potential problems such as uneven settlement or structural damage. These vibrations can cause undesirable effects on human well-being and safety, including discomfort, tiredness, and even health hazards in extreme cases.

In order to minimize the negative impact of vibration on both structures and occupants, effective vibration mitigation strategies are needed. Various damping systems, such as hydraulic, dry friction and dynamic dampers, have been proposed as practical solutions for absorbing and dissipating energy during seismic events or dynamic loads.

Thus, the study emphasizes the important role of vibration protection in ensuring the sustainability and well-being of both buildings and their occupants. Given the complex relationship between structural dynamics, soil properties, and human comfort, stakeholders can implement practical measures to improve the durability of buildings, reduce vibration-related risks, and protect the health and safety of people within the built environment.

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