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Cost Analysis of the Possibility of Securing an Energy-Efficient Building Against Harmful Effects of Vibrations on People

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Abstract. The aim of this article is to check vibrational comfort in near zero energy building (NZEB) which is often neglected for this type of building but could be annoying for residents. Building chosen for analysis is experimental building of Malopolska Laboratory of Energy Efficient Building which fulfils requirements for NZEB. The main advantage of this building is that it was design specially for research purposes and it has fourteen zones independently controlled. These zones give opportunity to ensure thermal, humidity, luminosity comfort, but do not measure vibrational comfort. Building is located in the city center of Krakow and very close to Szlak street on which cars and vans move. In this article the vibrational measurements carried out on the top floor of the building are presented. Results indicate that vibrational comfort should be taken into account in NZEB. Second part of the article describes possibility to ensure vibrational comfort in such a building by floor specially design for these purposes. In the city centres, vibro-acoustic floors could be the only solution when vibrational comfort during day or night is exceeded. Three different types of vibro-acoustic floor with different layers' configuration are described. Their advantages and disadvantages are also shown. In the end, cost analysis is made for different types of floor solutions and the most optimal solution is chosen. The selection is made not only by economic reasons but, above all, by functional premises. The floor solution chosen to be used in Malopolska Laboratory of Energy Efficient Building first of all should ensure the vibrational comfort during daytime because it is office building not residing in the night. The owners of the building will be offered an economic option that meets the requirements of vibrational comfort during the day and an exclusive option that will ensure that the vibration threshold of perception will be not exceeded.

1. Introduction

Requirements of near-zero energy building (NZEB) are the new part of designing buildings in European Union. Especially aspect of energy consumption imposes standards which should be fulfilled. The definition of the NZEB is described in [1]. NZEB is building of very high energy performance



determined in accordance with Annex 1 of [1]. In European Union countries, a deadline for implementing NZEB according to provisions of Article 9 of the Directive [1] for all new buildings was established for 1 January 2021. In 2021, the requirements will determine the Polish definition of NZEB. External partitions in buildings to fulfil stricter requirements should have values of heat transfer coefficient according to Table 1.

Table 1. Requirements of heat transfer coefficient values of building external partitions divided into years

Partition type	Heat transfer coefficient $U_{c(max)}$ [W/m ² ·K]		
	from 01.01.2014	from 01.01.2017	from 01.01.2021
External walls	0.25	0.23	0.20
Roofs and floors	0.20	0.18	0.15
Floor on the ground		0.30	
Windows	1.3	1.1	0.9
Door in external walls	1.7	1.5	1.3

Heat transfer coefficient ensures thermal comfort in the room [2]. The other aspects of comfort in the room are: humidity, lighting, indoor air quality (PM10, PM 2.5), acoustic and vibrational comfort. The last aspect of comfort is always neglected in analysis of room comfort. There are many researches that make many measurements in the field of building physics. Effects of humidity on human health and productivity in work were investigated in [3-5]. Lighting is also investigated even in aspect of different human activities [6-7], same as indoor quality [8-9] and acoustic comfort [10-11]. The problem is the lack of social awareness regarding the influence of vibrations on human body. Vibrations can not only be annoying but also in long duration period can have significant influence on human health. Low-frequency vibrations up to 25-30 Hz which are often generated by urban transport, because of its characteristics can be harmful. Low-frequency vibrations are close to resonant frequencies of internal human body organs [12] and can provide some medical symptoms which are listed in Table 2.

Table 2. Human body symptoms due to vibrations.

Symptoms	Frequency [Hz]
General feeling of discomfort	4-9
Head symptoms	13-20
Lower jaw symptoms	6-8
Influence on speech	13-20
“Lumb in throat”	12-16
Chest pains	5-7
Abdominal pains	4-10
Urge to urine	10-18
Increased muscle tone	13-20
Influence on breathing movement	4-8
Muscle constructions	4-9

There are three methods of evaluation of vibrational comfort in buildings [13, 14]:

- RMS (root mean squared) method
- MTVV (maximum transient vibration value) method
- VDV (vibration dose value) analysis

All three methods have advantages and disadvantages. RMS method is very good for designing because according this method results are in one third octave bands so structural engineer knows in

which frequency ranges comfort is exceeded. Disadvantage of this method is mean value which is improper to time history of acceleration with high value of crest factor. MTVV and VDV are similar methods but VDV is more accurate. This method is good for time history with peaks but it summarises all bands into one value, so it could be problematic for designers.

In this article NZEB chosen for analysis was investigated due to vibrational comfort because it is located nearby road in the city centre of Cracow. In some rooms of this modern building exceedance of vibrational comfort occurred and three types of vibro-acoustic floors were proposed as a solution of this problem. Cost analysis was also made to give an opportunity to the owner of the building to choose the most optimal solution.

2. Description of analysed building

Building selected to analysis is located in Cracow. It is reinforced concrete frame, five-storey building with typical for such a structure system of columns and floors. Building dimensions are 17.6 by 17.9m. The height of the building is 23.2m. Dimensions of structural components are as follows: columns are from 25 by 25 cm up to 35 by 35cm, floor slabs are 25cm thick. It is irregular building with concrete staircases located at the north side of the building. The view of the building is shown in Figure 1.



Figure 1. General view of the building

3. Measurement and result of RMS evaluation

The vibrational comfort measurements were made during 24h monitoring. There were two sources of vibrations: traffic from nearby road and controlled passage of truck. Appropriate instrumental set up was conduct for measurements and measurements points were located according to [13, 14] in the middle of the floors on the second and on the fifth floor in the rooms located into closer to dynamic excitation (road). Equipment and location of measurement point is shown in Figure 2.



Figure 2. Measurement point on the second floor

RMS method was chosen for evaluation because of its application in designing. During 24h monitoring 1447 vibration events were recorded with maximal acceleration values exceeding 3 cm/s^2 . Some of these vibrational events were confounded as a result of internal vibrations caused by residents of the building. Internal excitation signals were rejected from further analysis; however, over 1000 vibrational events still were analysed. In almost thirty events, the human perception threshold of vibration was exceeded on the second floor and in almost fifty events on the fifth floor. Exceedance always occurs in the vertical direction. Perception threshold of vibration according to [13,14] could be exceeded but the comfort level could not be. On the second floor in the five vibrational events comfort level was exceeded during the night, fortunately building chosen for analysis is an office building in which people do not stay during the night. Much worse situation occurs on the fifth floor in conference room located on this floor. Vibrational comfort in this room was exceeded not only during the night but also during the day which is unacceptable for office building. People working in such environment get tired faster and are less productive. In about 50 dynamical events comfort was exceeded in conference room located on the fifth floor. An example of RMS analysis for one of most harmful dynamical events is shown in Figure 3.

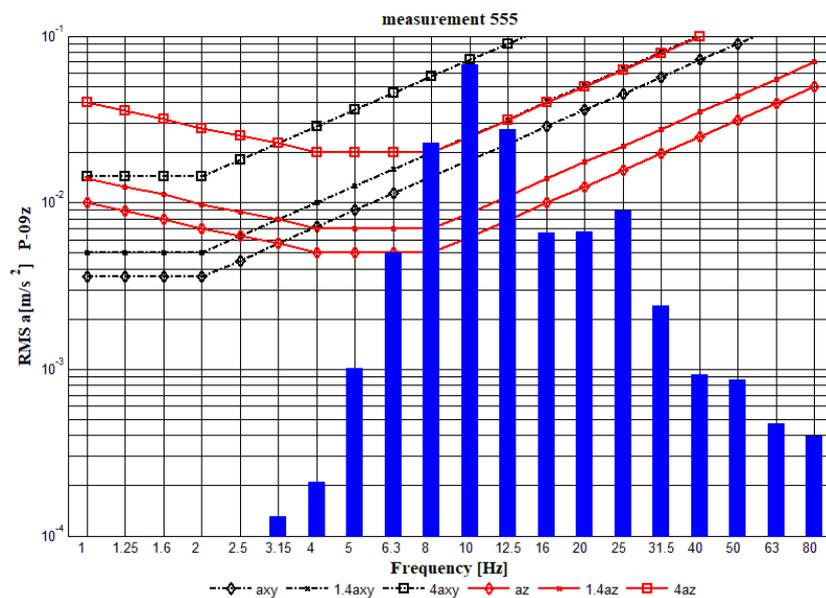


Figure 3. Result of the RMS analysis of acceleration record of vertical vibrations on the fifth floor

4. Possibilities of human's protection in building against vibration

Three variants of building protection are possible in terms of human protection against transport vibration.

4.1. *Vibration insulation in the source of vibration*

In this category we find mainly materials such as vibro-insulating mats for use under tramway tracks, railways and in the subway and vibro-insulation spacers in rails. Such vibration insulation is possible only at the stage of construction, reconstruction or repair of the track, which may cause problems. Additionally, it should be remembered that the railroad investor is responsible for such insulation, not the developer or owner of the property. There is no effective method of road insulation by using vibro-insulating materials.

4.2. *Vibration insulation on the way of propagation*

Vibration insulation on the way of propagation is carried out through well-designed ground partitions. Their structure and depth, width or distance from the building which will be protected should be design by structural engineer with great practice.

This solution is problematic for investors for two reasons:

- it is expensive and it requires a well-deigned design,
- investor should be the owner of the ground in which such a construction is build - in densely populated city centres this may be impossible. It is worth mentioned that ground partitions distance from the building is also design and that kind of construction mostly is built in a certain distance from protected building

4.3. *Vibro-insulation in the building*

In this case, the entire foundation slab or continuous footings are separated from the ground in a flexible manner (anti-vibration mat or by using special springs).

Vibro-insulation of the building causes problems for the investor due to the high costs of the project or the vibro-insulation material itself. Often, it also requires additional construction, which was not predicted in the original building design.

There is one solution for this type of vibro-insulation which could be an alternative for traditional insulation used in buildings – insulation of the floor. It could be implemented in three variants as is shown in Figure 4.

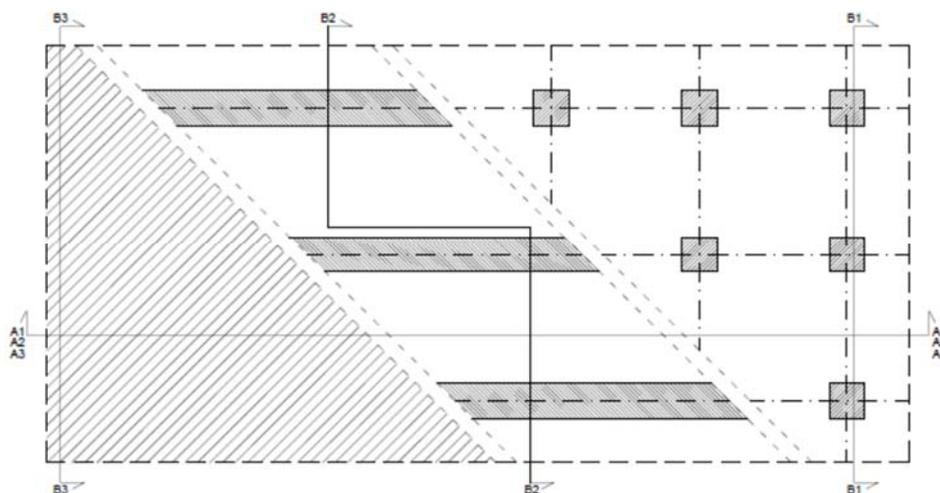


Figure 4. Three variants of floor vibro-insulation

4.4. The choice of vibro-insulation method

Because of the nearest neighbourhood of the local road the first solution is impossible. There is no vibro-insulation solutions for the source of vibration which is road. The second solution – partition in the ground is also impossible because of the distance between building and the road (Figure 5).

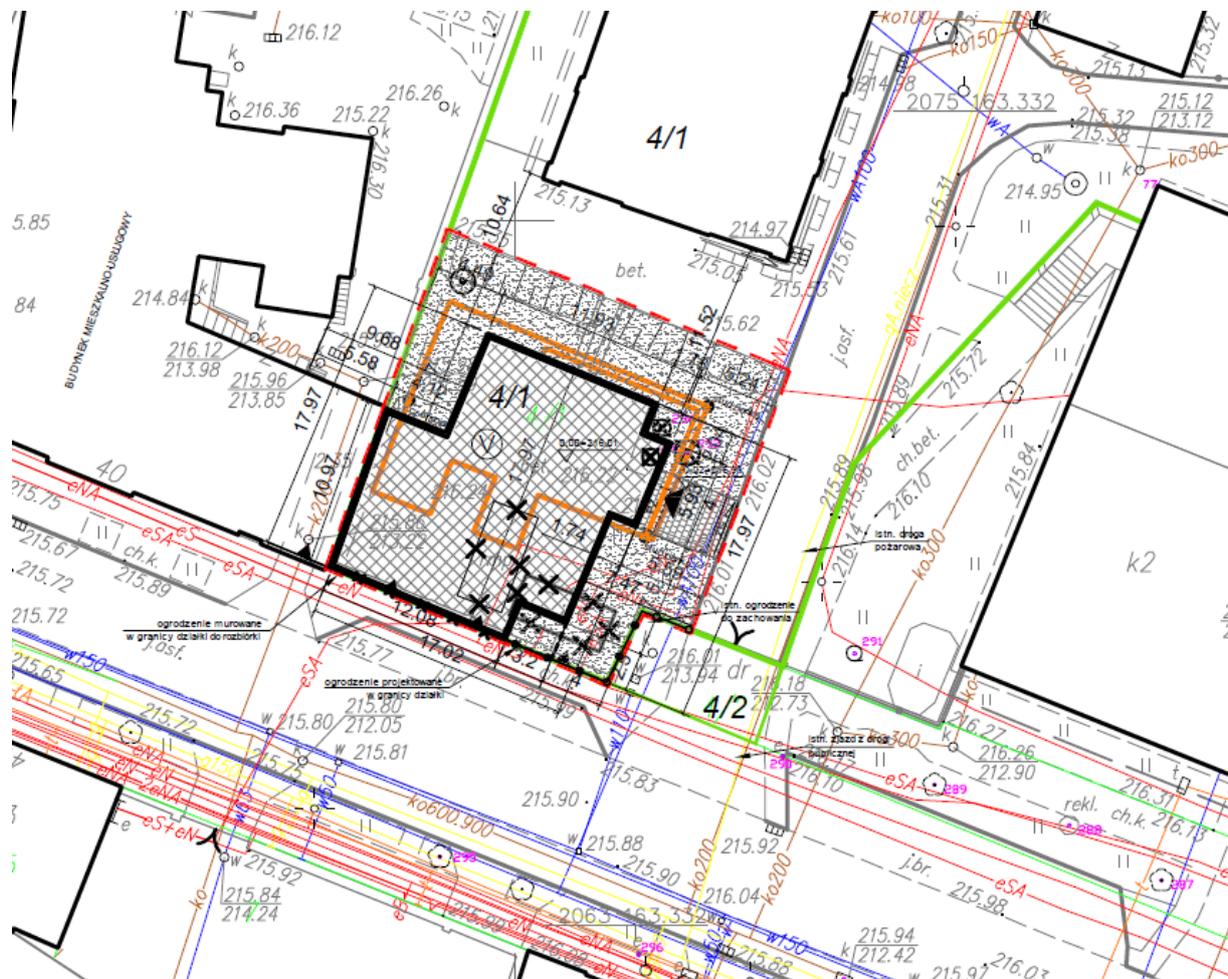


Figure 5. Localization of the building

The only one solution in this localization is the third variant of protection people against vibration – insulation in building. Because building already exist only one of vibroacoustic floor is proper for this purpose.

5. Results of cost analysis

Three different variants of vibroacoustic floor which are shown in Figure 4 differ significantly in price. The main cost of these variants is material which is vibro-insulating mat. Detailed calculation for 100 m² of the floor with the components of the cost is shown in the table 3. In the valuation the average prices of equipment, labour and overheads (indirect costs 65.4%, profit 10.8%, purchase costs 6.1% - due to this the material price jumped up) were adopted for the first quarter of 2018 from Sekocenbud [15].

Table 3. Cost calculations of three variants of vibroacoustic floor

Description	Unit costs	L	M	E
Variant 1 – mat on the whole floor KNR-W 2-02 1124-02_ Installation of vibro-acoustic mat				
Sum of direct costs 26516.22 EUR	265.1622	100.95	26399.84	15.43
Unit direct costs 265.1622 EUR		1.0095	263.9984	0.1543
Costs with overheads 26613.16 EUR	266.1316	185.04	26399.84	28.28
Unit cost 266.13 EUR		1.85	263.00	0.28
Variant 2 – mat strips under the joists KNR 19-01 0410-10_ Installation of hewn or hard wood joists KNR 9-12 0301-03_ Thermal and acoustic insulation made with mineral wool boards put between joists KNR-W 2-02 1124-02_ Installation of vibroacoustic material linearly in the strips				
Sum of direct costs 3953.61 EUR	39.5361	189.83	3745.41	18.37
Unit direct costs 39.5361 EUR		1.898	37.4541	0.1837
Costs with overheads 4126.95 EUR	41.2695	347.87	3745.41	33.67
Unit cost 41.27 EUR		3.48	37.45	0.34
Variant 3 – mat under the joists pointwise KNR 19-01 0410-10_ Installation of hewn or hard wood joists KNR 9-12 0301-03_ Thermal and acoustic insulation made with mineral wool boards put between joists KNR-W 2-02 1124-02 Installation of vibro-acoustic material pointwise				
Sum of direct costs 1618.27 EUR	16.1827	189.83	1410.05	18.39
Unit direct costs 16.1827 EUR		1.8983	14.1005	0.1839
Costs with overheads 1791.61 EUR	17.9161	347.87	1410.05	33.69
Unit cost 17.92 EUR		3.48	14.10	0.34

As can be seen from above Table the main component of the costs of vibro-acoustic floor, despite of high indirect costs, is cost of vibro-insulating mat. From this reason and for high vibro-insulation effectiveness the second variant was chosen to protect analysed building. The main problem of this solution is possibility of acoustic thrum occurrence because of existing empty interiors in the ceiling of that type. There is possibility to prevent such phenomenon by providing stone wool into empty interiors. Stone wool has proven its acoustic properties by usage in the roof. Unit cost of that kind of hybrid floor (with strips of mats under the joists and stone wool in empty interiors) would have to increase by about 5-10 EUR but total costs will not exceed 50 EUR/m².

There is of course possibility that only in this rooms in which vibrational comfort level is exceeded vibro-acoustic floor will be installed. Measurements made on the fifth floor indicate that on that floor residents should be protected but on the second floor comfort level is exceeded only during the night and because analysed building is an office building in which people do not stay during night.

6. Discussion and conclusions

Nowadays there is a trend to minimize costs of structural elements. Construction of course have to meet standards requirement but in the minimum way. During this process some of comfort aspects are neglected. Fashionable issues in construction is thermal comfort [4], humidity [3], and attention is increasingly being paid to noise problems [11]. Vibrational comfort is always neglected till residents of building start complaint [16].

When building already exists is much harder to protect residents from vibrations specially caused by road excitation [17]. The costs of installation of additional floor are very high what is shown in the article. To protect fully residents of analysed building the best solution is the first variant with vibro-insulating mat on the whole floor, but this is the most expensive variant which cost about 266 EUR/m². That kind of cost could be acceptable for representative high class buildings or in laboratory with very sensitive equipment. The second variant is an optimal variant for this office building. The cost is medium (about 40 EUR/m²) and by adding additional stone wool can protect residents against vibrations and noise including impact sounds (total cost with stone wool is about 50 EUR/m²). The third solution, the cheapest one, was not taken into account because more analysis and measurements especially on real structure should be made to prove effectiveness of that solution.

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