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Analysis of rail traffic vibrations' impact on a residential building. A case study.

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Abstract: This paper presents an analysis of the harmful effects of vibrations caused by train traffic in the area of the Radzionków train station and transmitted through the substrate soil to a neighbouring residential building. Mechanical vibrations caused by train traffic were assessed pursuant to the requirements specified in the Polish PN-B-02170:2016-12 standard and compared with the standard threshold values. The research methodology, taking into account a description and location of the measurement site and specification of the measurement apparatus, is also presented.

Keywords: rail traffic vibrations, substrate soil, impact on a building.

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1. Introduction

Residential buildings located close to traffic routes – railways or roads – are exposed to dynamic impacts caused by traffic. Buildings dating from before World War II are often found in close proximity to traffic routes. The location of these buildings stems from low traffic volumes and narrower roads in the past. With the development of domestic and foreign road and rail transport, the hazard resulting from vibrations arising during the movement of large loads has increased in recent years.

Being aware of the impact vibrations are exerting on existing buildings, as well as on the people living therein, is very important for using these buildings. This is because vibrations have an impact on the technical condition of a building, operating costs and reduce the safety and comfort of the people living in them.

Ground vibrations exceeding the acceptable parameters, propagated by the ground to the urban environment (such as buildings) will have a tendency to generate deformations (Yuan et al., 2011), cracks on surface structures and may cause walls and floor-ceiling assemblies to vibrate (Connolly et al., 2016), (Yang et al., 2018). Any potential vibration parameter analyses should not overlook the impact of vibrations on people within those buildings – residents may be exposed to dynamic effects generated by underground works but also by above and underground factors which constitute background vibration at different frequency ranges (Vladimir et al., 2017). Building diagnostics and design increasingly more often call for the above effects to be taken into account together with a verification of whether building requirements have been met in terms of vibration comfort for individuals in those buildings (Kawecki and Kowalska-Koczwara, 2011).

One of many standards can be applied to assess the negative impact of traffic vibrations on residential buildings. The following are the most commonly used standards in Poland:

- the German DIN 4150-3 "Structural Vibration Part 3: Effects of vibration on structures (in German)";
- the Polish PN-B-02170:2016-12 "Assessment of the harmfulness of vibrations transmitted through the ground onto buildings" (in Polish).

The Polish standard facilitates a more comprehensive assessment of a building's vibration situation. A proximate analysis of the harmful effects of vibrations relies on the dynamic impact scale (SWD) for two types of buildings:

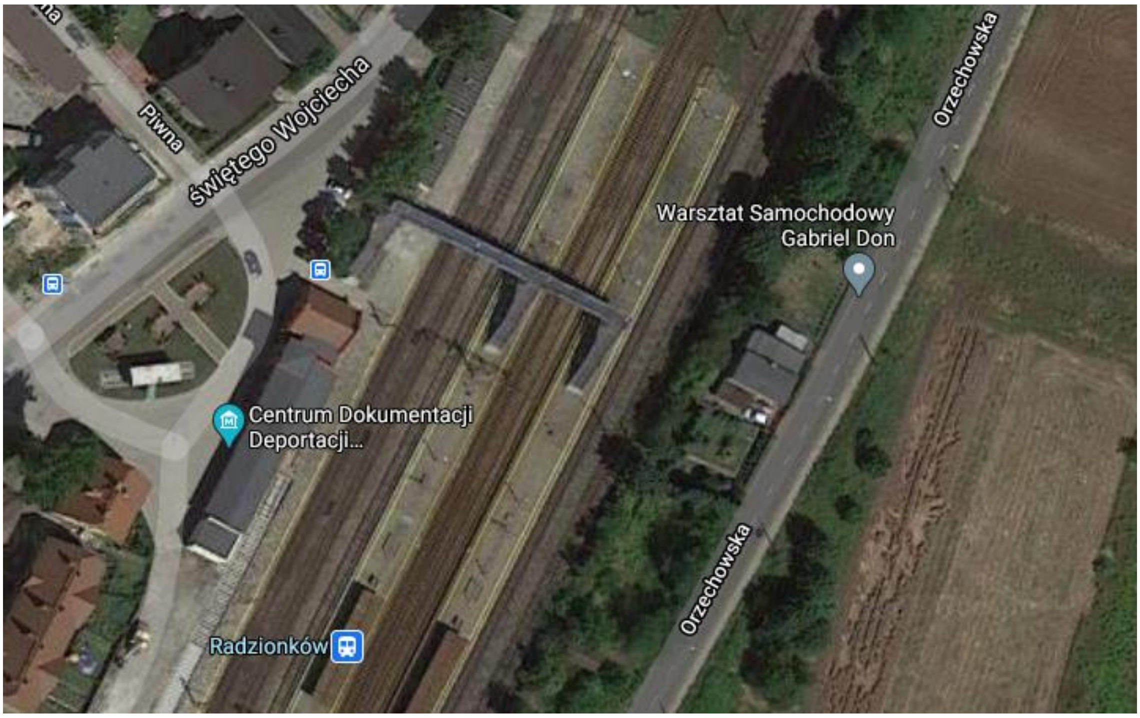
- SWD-I – small buildings with a compact footprint and up to two storeys high;
- SWD-II – buildings with a maximum of five storeys, which are smaller than twice the width.

A vibrations impact assessment was carried out on the basis of the Polish PN-B-02170: 2016-12 standard, which is based on an analysis of changes in acceleration amplitude as a function of frequency. The standard groups intensity of the analysed vibrations into five harmful zones:

- zone I – vibrations imperceptible to a building;
- zone II – vibrations discernible by a building's finishing elements (initial cracks in plasters and mortars) resulting in accelerated wear and tear of a building but not harmful to its load bearing structure;
- zone III – vibrations harmful to a building's load bearing structure, resulting in local hairline cracks and cracks to construction and structural elements including crumbling of plasters and mortars, which weaken the load bearing structure, its integrity and resistance to subsequent dynamic factors;
- zone IV – vibration load very harmful to a building, posing a safety risk within the scope of human habitation on account of numerous cracks and local damage, including destruction of masonry partitions and other individual construction and structural building elements, risk of suspended items falling, plasters crumbling from ceilings, ceiling beams dislodging from supports, etc.;
- zone V – vibrations cause a risk of a building collapse, a building may not be used.

2. Building specification

Rail traffic vibrations impact on buildings assessment was performed using a residential building located in Radzionków as an example – Photograph 1. It is a brick building with two above-ground and one underground floor erected in 1934. The structure of the building has cracks and gaps in internal and external plasters – Photographs 2-5. The vibrations are caused by the train traffic along railway tracks in the area of the Radzionków train station. The closest track runs approximately 12 m from the building. "In situ" measurements were made between 20.01.2021 and 27.01.2021.



Photograph 1. Location of the building (source: https://www.google.pl/maps).

Photograph 2. Visible crack under repair in the façade plaster starting at the upper corner of the window opening.

Photograph 3. Visible hairline diagonal crack in the façade plaster ending at a point where a lamp is attached.

Photograph 4. Visible façade plaster cracks in a section where the wall is weaker due to window openings.

Photograph 5. Visible diagonal façade plaster crack in a section where the wall is weaker due to window openings.

3. Research methodology

The paper was written on the basis of the following legal acts and source materials:

- Regulation of the Polish Minister of Infrastructure and Construction of November 14th, 2017, amending the regulation on technical conditions of buildings and their location (Journal of Laws 2017, item 2285),
- PN-B-02170:2016-12 Assessment of the harmfulness of vibrations transmitted through the ground onto buildings,
- site visit on 14.01.2021,
- measurements taken between 20.01.2021 and 27.01.2021,
- information and materials provided by the principal.

The impact assessment of vibrations on buildings was carried out according to the approximate method based on the PN-B-02170:2016-12 standard. The building subject to analysis satisfies the SWD-I scale applicability criteria. An analysis of vibration acceleration intensity was performed in 1/3 octave bands in the range of 1 to 100 Hz.

Vibrograms of vibration acceleration as a function of time obtained from the load bearing structure of the building at selected measurement points with respect to two mutually perpendicular X and Y axes were used for the analysis. A 750 Hz sampling frequency digital signal was used to capture data (includes the useful 375 Hz frequency band). Single vibro-acoustic events were extracted from the recorded waveform after applying low-pass filtering with a cut-off frequency of 120 Hz. Vibration duration was then determined in accordance with the PN-B-02170:2016-12 standard. A spectrum of peak values was determined for each vibration period.

Measurements were taken at two measurement points PP.1 and PP.2 located at the intersection of structural walls at the underground floor level on the side of the vibration source – Fig. 1 and 2.

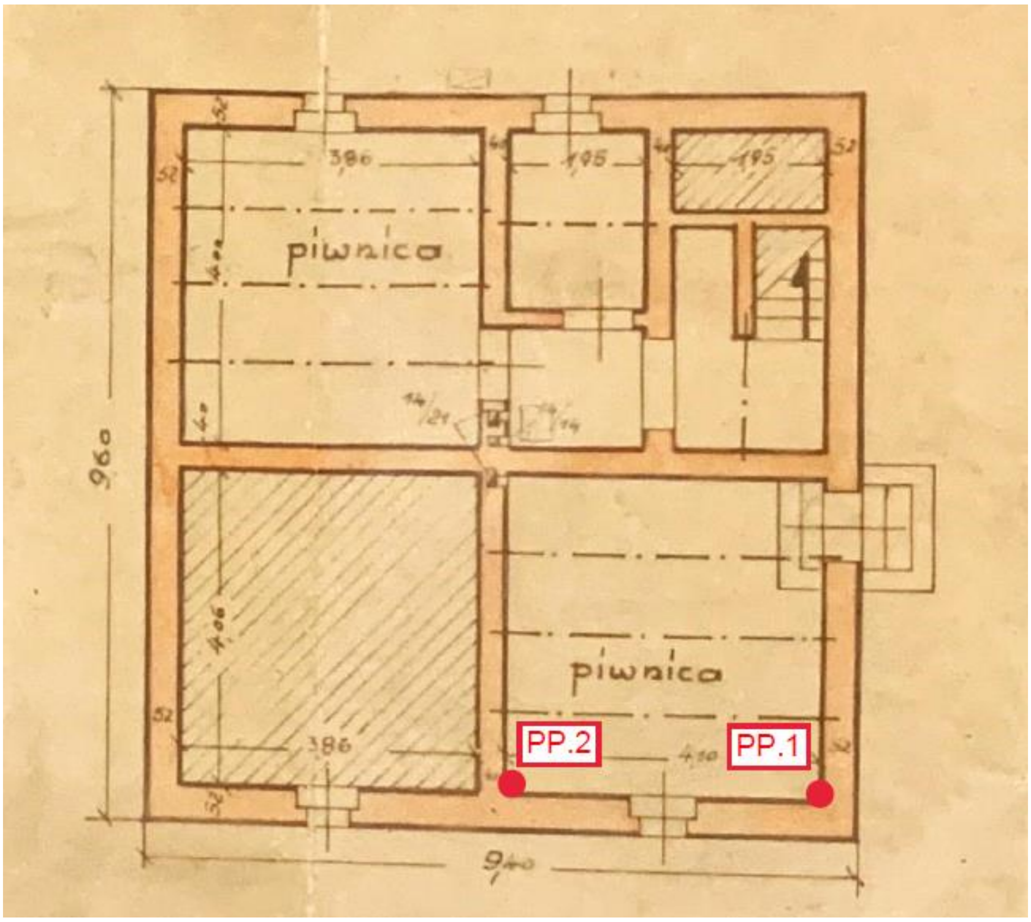


Fig. 1. Location of measurement points – an underground floor plan of the building.

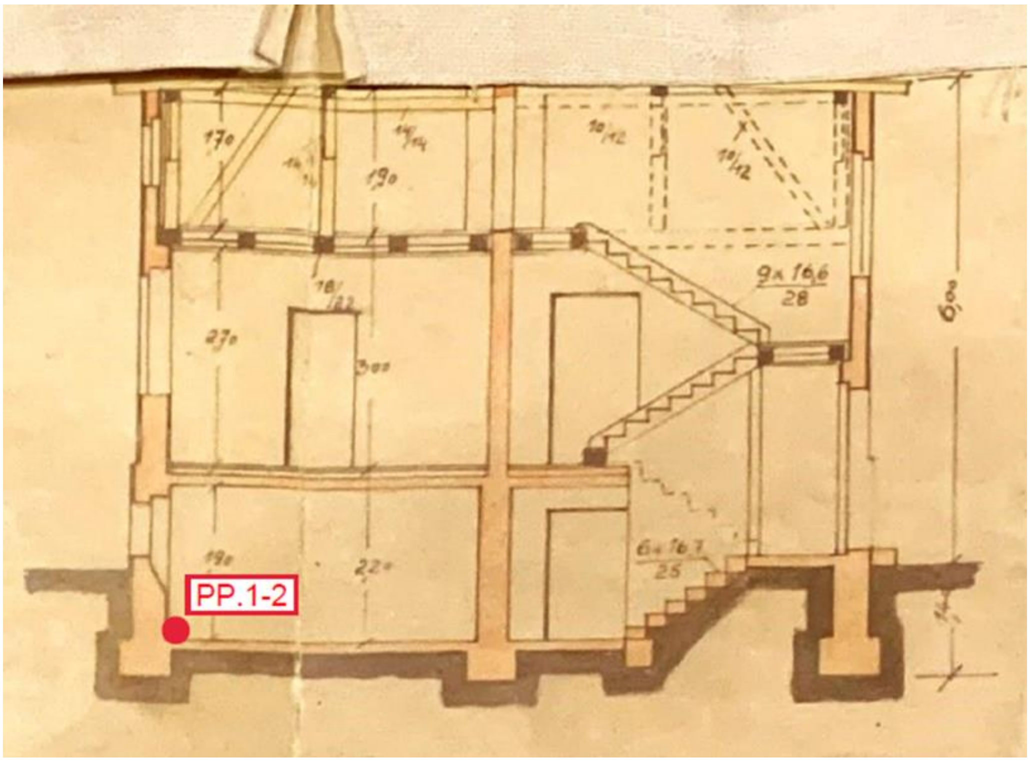


Fig. 2. Location of measurement points – building cross-section.

Alignment of measurement axes:

- X axis (CH1 channel) – horizontal, parallel to the railway line;
- Y axis (CH3 channel) – horizontal, perpendicular to the railway line;
- Z axis (CH2 channel) – vertical.

Apparatus used to measure vibrations:

- SVAN 958A No. 34581 vibration and noise level meter, together with SV 84 No. H0364 vibration accelerometer (calibration certificate 00016242/10/2020 of 2020-09-07);
- SVAN 958A No. 36683 vibration and noise level meter, together with SV 84 No. C6143 vibration accelerometer (calibration certificate 00016244/10/2020 of 2020-09-07);
- SV111 No. 30596 vibration calibrator (calibration certificate 628/06/2018 of 2018-08-22);
- SVAN PC++ software;
- hardware and cabling.

Vibration accelerometers were attached to the building (wall) using construction grade gypsum.

4. Measurement results

The measurement chain was validated before measurements were carried out. The results are shown in Table 1:

Table 1. Measurement chain validation results

Measuring instrument	Validation	Validation result [m/s2]			Reference value [m/s2]
		Ch1	Ch2	Ch3	
SVAN 958A No. 34581	Before measurement	0.983	0.984	0.997	0.99
	After measurement	0.983	0.984	0.997	
SVAN 958A No. 36683	Before measurement	0.982	0.978	0.979	0.99
	After measurement	0.982	0.978	0.979	

The measurements were taken in a closed room on "-1" floor – Figures 1 and 2. Access to the room was restricted for the duration of the measurement to avoid interference. The only technical device in the room was a coal furnace. Its operation did not affect the recorded waveforms. Table 2 below shows the environmental conditions recorded in the room during the measurements.

Table 2. Measurement conditions

	Maximum values	Minimum values	Mean values
Ambient temperature [^{o}C]	22.1	15.2	21.5
Atmospheric pressure [hPa]	972.5	956.7	963.8
Relative humidity [%]	51.3	31.7	34.3
Wind speed [m/s]	0.0	0.0	0.0
Comments:	-		

The vibro-acoustic signal was registered continuously during the measurements. 477 events caused by rail traffic (train passage, stops, departures of passenger and freight trains, locomotives and special cars) and maintenance works in the area of Radzionków railway station were extracted.

6 events with the highest WODB (building vibration perception index) value were selected for presentation. The diagrams in Figs. 3-8 below show vibrograms for one of the 6 aforementioned events – Table 3. All the events presented were connected with the passage of freight trains along a rail track closest to the building – photograph 6.

Photograph 6. Freeze-frame from a video recorder 12:18:33 27.01.2021.

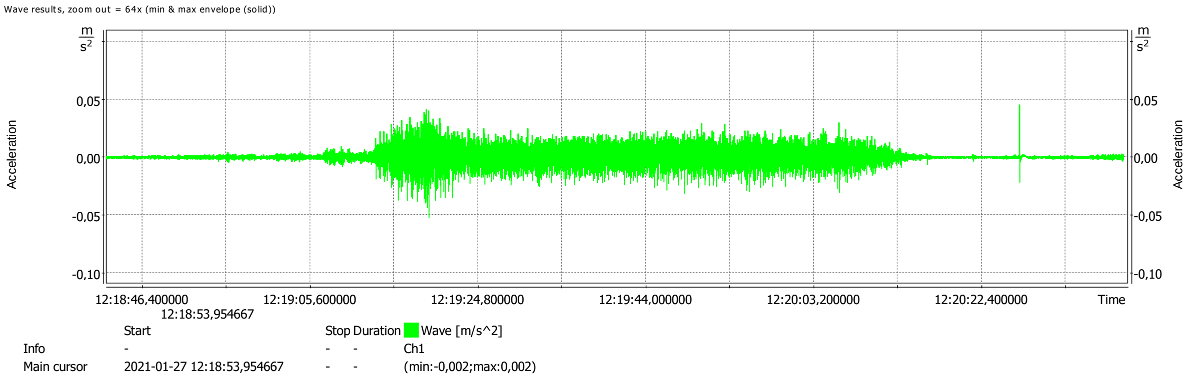


Fig. 3. Event vibrogram registered on 27.01.2021 at 12:18 p.m. – PP.1, X axis, Ch1 channel.

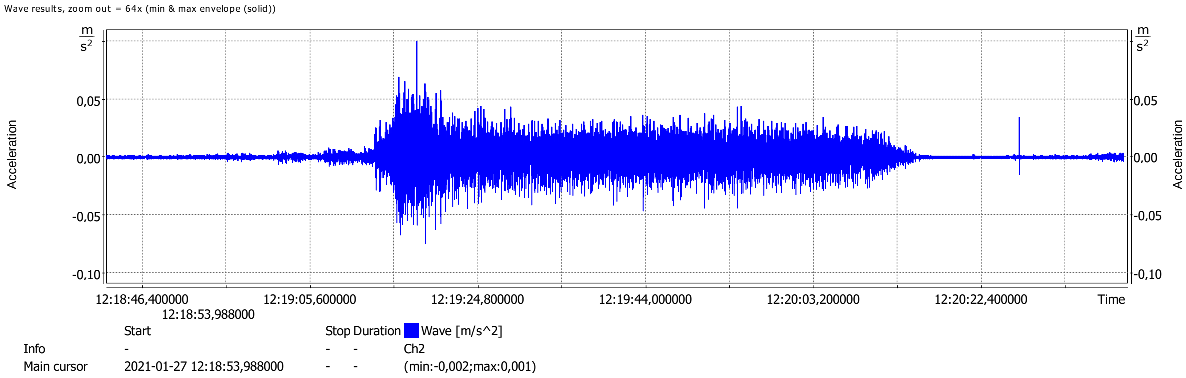


Fig. 4. Event vibrogram registered on 27.01.2021 at 12:18 p.m. – PP.1, Z axis, Ch2 channel.

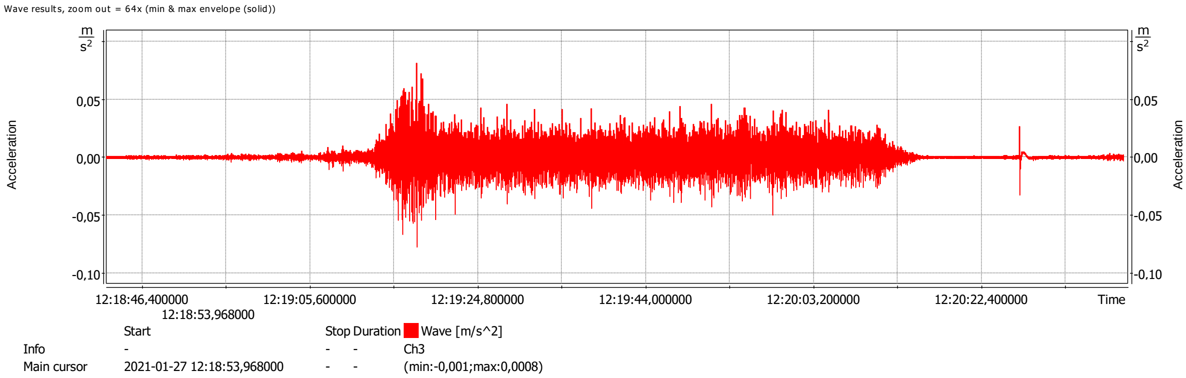


Fig. 5. Event vibrogram registered on 27.01.2021 at 12:18 p.m. – PP.1, Y axis, Ch3 channel.

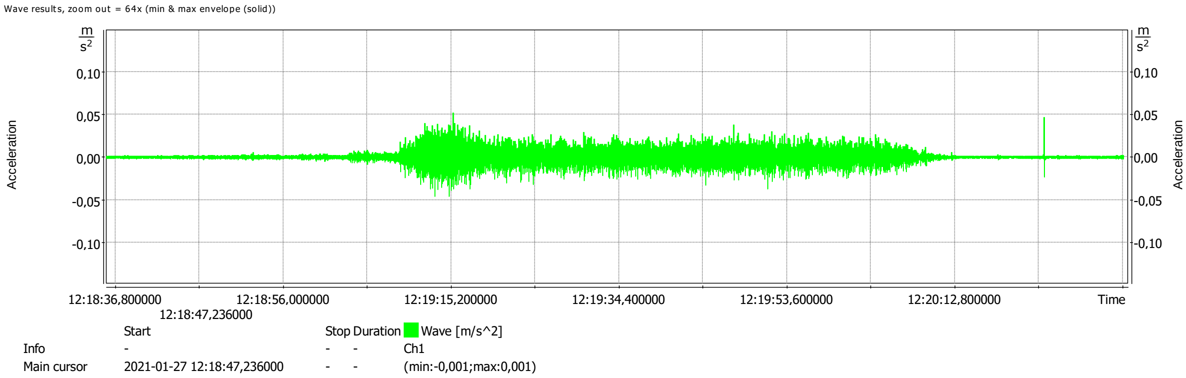


Fig. 6. Event vibrogram registered on 27.01.2021 at 12:18 p.m. – PP.2, X axis, Ch1 channel.

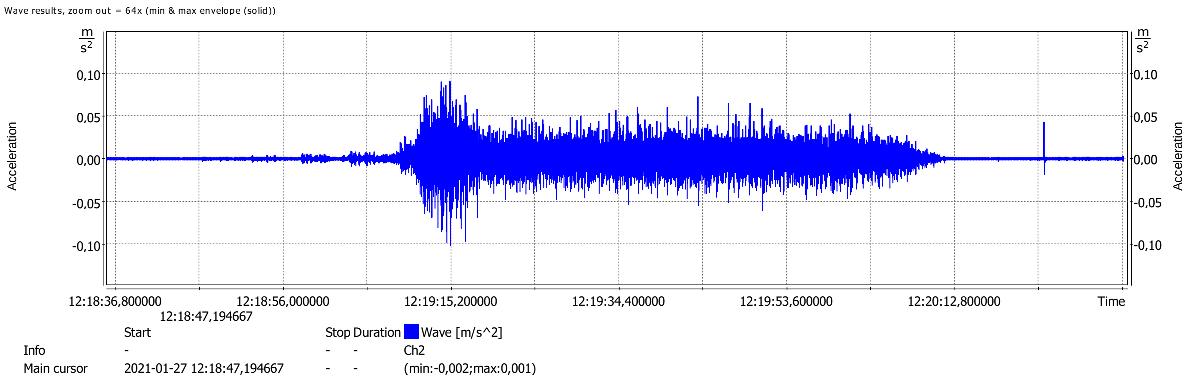


Fig. 7. Event vibrogram registered on 27.01.2021 at 12:18 p.m. – PP.2, Z axis, Ch2 channel.

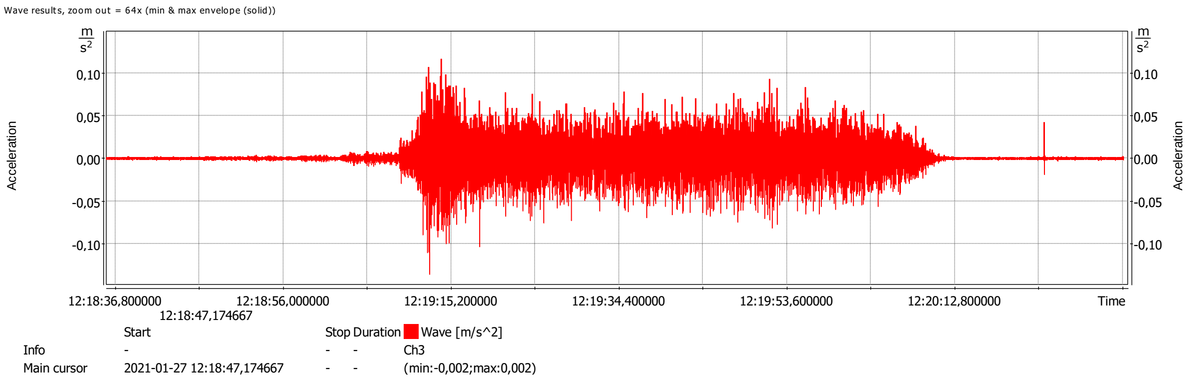


Fig. 8. Event vibrogram registered on 27.01.2021 at 12:18 p.m. – PP.2, Y axis, Ch3 channel.

Table 3. Measurement results of harmful vibrations transmitted from the ground to the building

Measurement point	X axis		Y axis	
	Event time	WODB building vibration perception index	Event time	WODB building vibration perception index
PP.1	2021-01-22 02:05:27,081	0.59	2021-01-22 02:05:25,861	0.97
PP.1	2021-01-22 16:15:40,485	0.41	2021-01-22 16:15:40,485	0.76
PP.1	2021-01-26 17:51:56,928	0.56	2021-01-26 17:51:55,094	0.77
PP.1	2021-01-27 01:12:37,180	0.89	2021-01-27 01:11:41,920	1.66
PP.1	2021-01-27 12:20:11,285	0.51	2021-01-27 12:20:12,418	0.93
PP.1	2021-01-27 19:51:10,483	0.52	2021-01-27 19:51:09,286	0.66
PP.2	2021-01-22 02:05:28,106	0.63	2021-01-22 02:05:25,857	1.09
PP.2	2021-01-22 16:16:19,306	0.52	2021-01-22 16:16:18,329	1.08
PP.2	2021-01-26 17:51:53,173	0.54	2021-01-26 17:51:51,896	1.04
PP.2	2021-01-27 01:12:35,491	0.74	2021-01-27 01:11:09,630	2.12
PP.2	2021-01-27 12:20:08,954	0.57	2021-01-27 12:20:09,342	1.61
PP.2	2021-01-27 19:51:06,698	0.49	2021-01-27 19:51:04,920	1.39

5. Analysis of the results

For the applied vibration acceleration measurement methodology, the estimated value of the expanded uncertainty level U95 is 10.4%. Compliance with the requirements of the PN-B-02170:2016-12 standard was confirmed by a Research Laboratory by relating the result directly to the normative requirements without taking into account measurement uncertainty. The applied simple acceptance principle entails a 50% risk level associated with false acceptance or false rejection of the obtained results.

Tables 4 and 5 below present the highest vibration acceleration values recorded at a given measurement point, in particular 1/3-octave bands and the determined building vibration perception index (WODB) together with the centre frequency of the frequency band which registered the highest ratio of maximum vibration acceleration to the acceleration corresponding to the lower limit of allowance for dynamic effects (fWODB).

Table 4. Measurement results of vibrations transmitted from the ground to the building.

MEASUREMENT RESULTS – measurement point PP.1			
f [Hz]	Peak vibration acceleration value a_{peak} [m/s^2]		
	X	Y	Z **not assessed**
0.8	0.00091	0.00175	0.00011
1	0.00030	0.00082	0.00019
1.25	0.00036	0.00083	0.00026
1.6	0.00043	0.00085	0.00036
2	0.00051	0.00081	0.00042
2.5	0.00072	0.00082	0.00056
3.15	0.00088	0.00080	0.00067
4	0.00111	0.00093	0.00084
5	0.00167	0.00109	0.00187

MEASUREMENT RESULTS – measurement point PP.1			
f [Hz]	Peak vibration acceleration value a_{peak} [m/s^2]		
	X	Y	Z **not assessed**
6.3	0.00607	0.00399	0.00332
8	0.00450	0.00533	0.00348
10	0.00681	0.00577	0.01048
12.5	0.00883	0.00977	0.01816
16	0.01627	0.01080	0.03069
20	0.01140	0.01570	0.03273
25	0.01388	0.03528	0.02907
31.5	0.02924	0.03315	0.01834
40	0.02679	0.06152	0.02475
50	0.01897	0.03346	0.03681
63	0.02928	0.03963	0.05164
80	0.01809	0.02080	0.05052
100	0.02170	0.01888	0.01884
WODB	0.89	1.66	1.64
f_{WODB} [Hz]	31.5	25.0	20.0

For a 95% confidence interval the measurement results are subject to expanded uncertainty of 10.4% for a coverage factor of k = 2.

The graphs shown in Figures 9 and 10 show the highest peak vibration acceleration values with respect to the SWD-I scale.

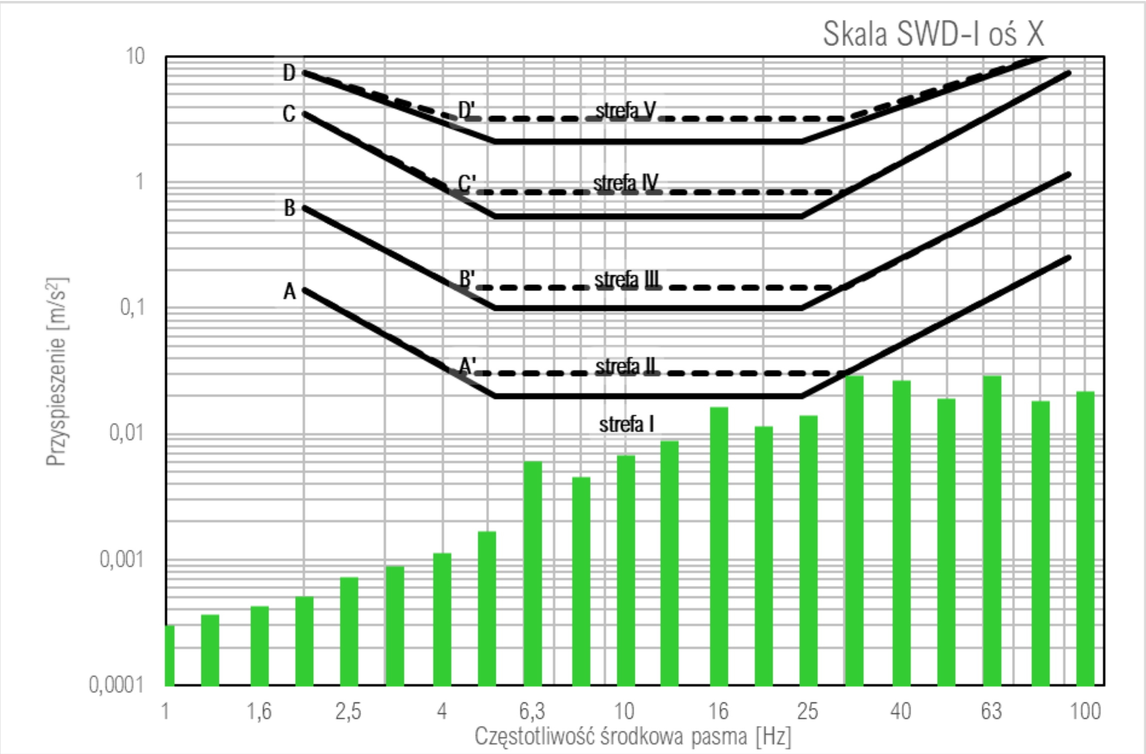


Fig. 9. Vibration acceleration measurement results along the X axis, SWD-I scale of the building – PP.1 measurement point.

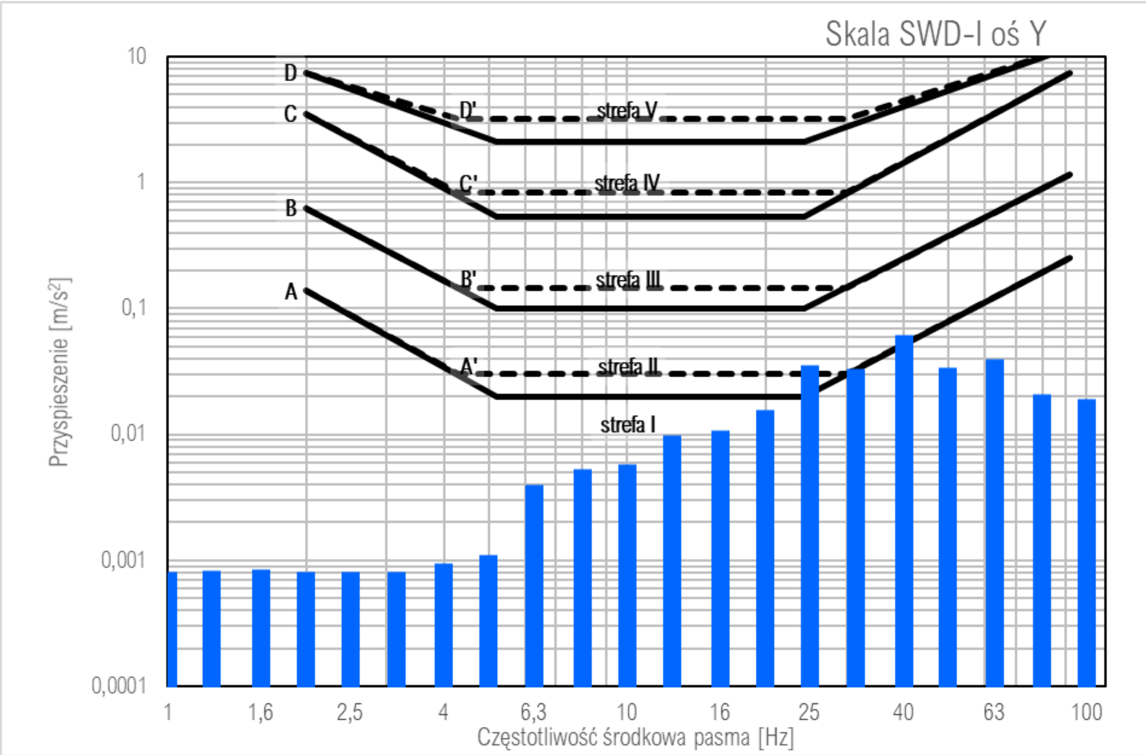


Fig. 10. Vibration acceleration measurement results along the Y axis, SWD-I scale at ul. Orzechowska 66 – PP.1 measurement point.

Table 5. Measurement results of vibrations transmitted from the ground to the building.

MEASUREMENT RESULTS – measurement point PP.2			
f [Hz]	Peak vibration acceleration value a_{peak} [m/s^2]		
	X	Y	Z **not assessed**
0.8	0.00060	0.00475	0.00714
1	0.00073	0.00531	0.00955
1.25	0.00071	0.00533	0.00882
1.6	0.00041	0.00168	0.00320
2	0.00051	0.00119	0.00311
2.5	0.00054	0.00113	0.00310
3.15	0.00054	0.00114	0.00303
4	0.00078	0.00121	0.00289
5	0.00156	0.00139	0.00333
6.3	0.00453	0.00368	0.00351
8	0.00434	0.00421	0.00366
10	0.00682	0.00557	0.00919
12.5	0.01125	0.00832	0.01626
16	0.01442	0.01233	0.02864
20	0.01172	0.01979	0.04310
25	0.01570	0.04513	0.04858
31.5	0.02427	0.05715	0.02812
40	0.03846	0.09162	0.03400
50	0.01919	0.05534	0.04683

MEASUREMENT RESULTS – measurement point PP.2			
f [Hz]	Peak vibration acceleration value a_{peak} [m/s^2]		
	X	Y	Z **not assessed**
63	0.02854	0.08395	0.03972
80	0.01928	0.04989	0.04406
100	0.02249	0.02532	0.02413
WODB	0.74	2.12	2.28
f_{WODB} [Hz]	40.0	25.0	25.0

For a 95% confidence interval the measurement results are subject to expanded uncertainty of 10.4% for a coverage factor of k = 2.

The graphs shown in Figures 11 and 12 show the highest peak vibration acceleration values with respect to the SWD-I scale.

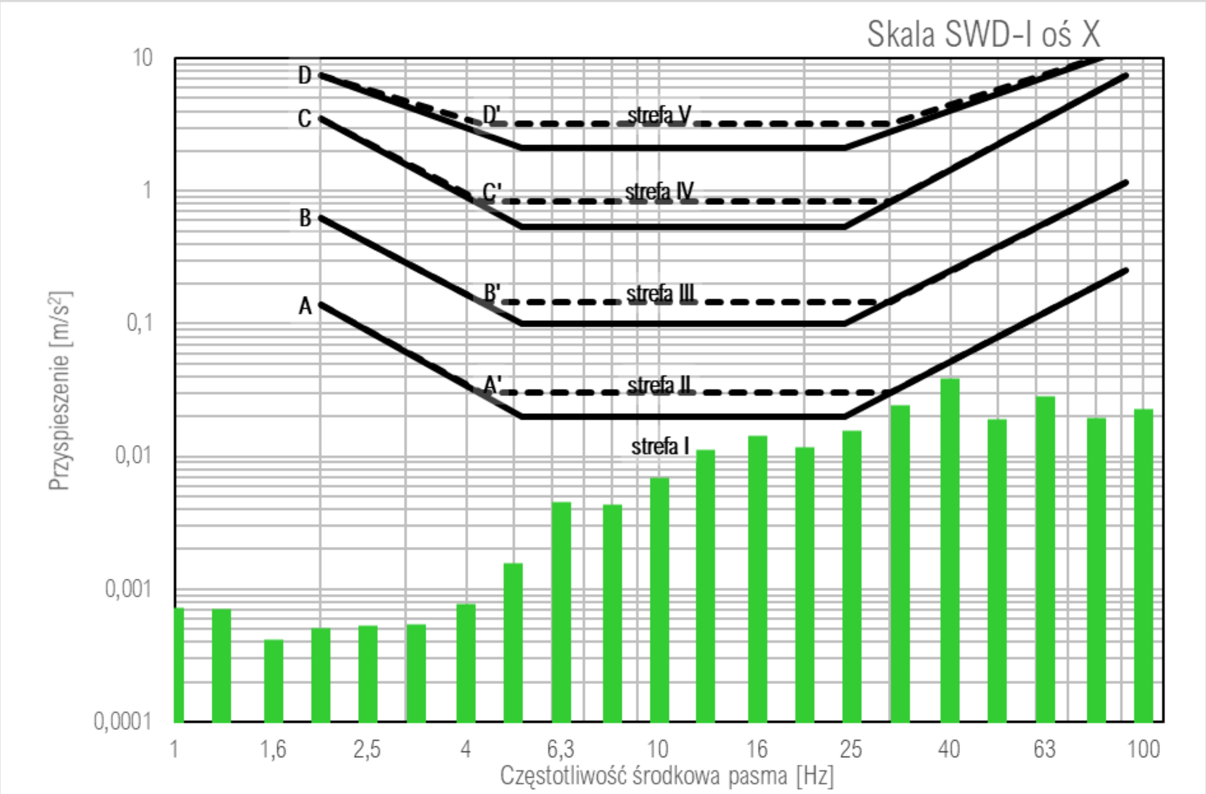


Fig. 11. Vibration acceleration measurement results along the X axis, SWD-I scale of the building – PP.2 measurement point.

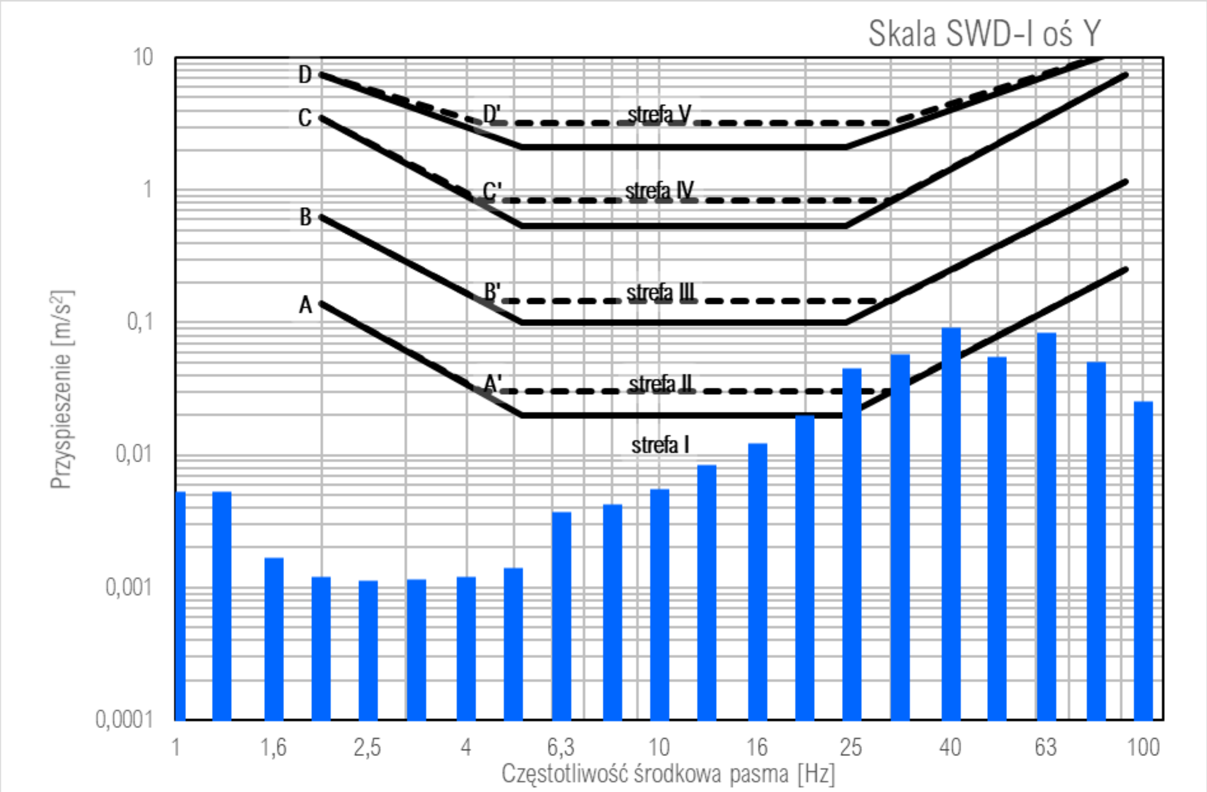


Fig. 12. Vibration acceleration measurement results along the Y axis, SWD-I scale – PP.2 measurement point.

As a result of the analysis, vibration acceleration values were found to be in zone II of the SWD-I scale.

6. Conclusions

According to the performed measurements and analysis, vibration acceleration values registered in the building are in zone II of the SWD-I scale according to the Polish PN-B-02170:2016-12 standard "Assessment of the harmfulness of vibrations transmitted through the ground onto buildings" – vibrations harmless to a structure; however, accelerated wear and tear of the building in question and first cracks in plasters and mortars, wall corners and facets, etc. can be expected. As the effect of the vibrations on the building in question in long-term, symptoms mentioned in the standard in the form of cracks in the plaster and mortars have already appeared.

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