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Analysis of the Vibration Propagation Induced by Pulling out of Sheet Pile Wall in a Close Neighbourhood of Existing Buildings

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Abstract
The paper presents the results of research involving the measurement of vibration acceleration generated during the extraction of elements of sheet pile wall. The study was conducted at four measurement points in three mutually perpendicular directions. Three measurement points were located on the ground, the fourth point was taken on the wall of the building. The analysis of evaluation of the influence of vibration transmitted to the building were also conducted. It was confirmed that the vibration monitoring is necessary in the initial phase of work associated not only with the hammering of steel sheet pile walls but also in the process of dismantling.

Keywords: underground communication object, measurement of vibrations, propagation of vibrations in the subsoil

1 Introduction

Construction equipment used in the course of investments related to the construction, modernization and repairs of road and rail infrastructure, usually is a source of vibrations propagated to the environment. Depending on the type of works and equipment used, particular types of works may induce vibrations of very high amplitudes and low frequencies (e.g. driving piles into soil) or vibrations of relatively low amplitudes and high frequencies (e.g. vibratory driving and pulling out of sheet pile wall components, operation of rollers, vibratory plates, etc.). From the point of view of the impact of vibrations propagated by the subsoil on buildings located in the immediate vicinity of ongoing investments and their users, the most unfavourable vibrations have frequencies similar to the basic, dominant and natural frequencies in these objects (the risk of resonance vibrations). Machines and devices which are the source of vibrations propagated to the environment should also be selected in this respect. Unfortunately, in reality, both the investor and the contractor, as well as building administrators

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do not have sufficient data to allow appropriate selection of the type of devices and its working parameters so that the effects of vibrations propagated on buildings and their users were minimal. Failure to adjust the equipment in terms of type and the parameters of generated vibrations to local conditions (e.g. distance of the works from a building, its type and technical condition, etc.) can lead not only to a deterioration of comfort of using the buildings, but also to their damage. Usually such damages do not develop into a major accident in the construction of buildings, but are only typical of the accelerated tear and wear, cracking plaster and rendering. In cases when there is evidence that the damage to a building or complex of buildings was caused by excessive vibration propagated from a construction investment works it is the responsibility of the developer to cover the cost of necessary repairs.

Approximate distances, in which there should be no damage to buildings as a result of propagation of vibrations are given in Polish Standard PN-85/B-02170. These are obviously approximate values and apply only to traffic vibration. Unfortunately there are no similar lines of code regarding minimum distances from buildings in which it would be safe to vibratory drive sheet pile walls, or drive piles for the foundations of bridges or other building structures. Hence, there is need for further systematic work on the propagation of this type of vibration in the ground – especially in difficult ground conditions: high ground water level, numerous intercalations, etc.

While the subject of vibrations generated during driving piles for the foundations, or vibratory driving of sheet pilings has been studied by many researchers worldwide (e.g. Masoumi et al., 2007; Athanasopoulos et al., 2000; Jastrzebska et al., 2014) the issues related to the propagation of vibration generated during the vibratory pulling of the sheet pilings have been treated with significantly less attention. The result of this state of affairs is the widespread belief that the vibration accompanying vibratory pulling of sheet pilings is much less intensive, and thus much less harmful to the environment. So it should not be surprising that in practice the engineering works related to vibratory pulling of the sheets is often conducted without reasonable care and diligence – many a time at the maximum possible amplitudes of vibration. Such action could lead to even more serious damage to buildings neighbouring with construction site than during vibratory driving of sheet piles.

The aim of this study is to present the authors' own research results related to the implementation of vibration acceleration measurements conducted during vibratory pulling of the sheet piling elements and to analyse a possible impact of the recorded vibration acceleration waveforms on the technical condition of a residential building located in the immediate vicinity of the source of vibration.

2 Measuring Location

The selected measuring location was the area of construction works of a subway at the intersection of Sienkiewicza St. and Pilsudskiego St. in Bialystok. Due to the quite varied soil conditions and high groundwater level at the location of the underpass and the proximity of the Biala River, as early as at the design stage it was decided that sheet pile wall will be constructed around the boundaries of the subway in order to prevent flooding of the building site. Subsoil consisted of the following layers: 0-2.0 m – embankment without compaction control, 2.0-2.9 m – silt (liquidity index $I_L = 0.20$), and 2.9-5.0 m – fine sand (relative density $I_D = 0.40$). The water content of the ground in the area of surface propagation was low, hence the water content does not substantially affect the level of vibration. Ground waters in the subsoil at the test site were reaching a depth of approx. 3 m. The decision to use sheet pile walls was also influenced by the necessity to protect the walls of the trench due to the proximity of residential-service buildings and hence the risk of possible damage to these buildings. There were, however, concerns regarding possible damage to nearby non-building structures due to the propagation of vibration accompanying driving of sheet pile walls into the ground. Therefore, a decision was taken to apply a method of partial static pressing of sheet piles, what subsequently prevented further damage to the surrounding buildings. The contractor did not have similar concerns about excessive levels of vibration at the stage of pulling out of the sheet piles. The authors of this study conducted field research related to the propagation of vibrations in the ground during vibratory pulling out of sheet pile walls concluded with an approximate assessment of the impact of these vibrations on nearby buildings.

A 4-point measuring profile was set in a straight line between one of the pulled sheet pile walls and a four-storey, residential – commercial, masonry building with converted loft. At each point the acceleration of vibration was recorded in three mutually perpendicular directions (x, y, z – respectively: in the horizontal plane, along and perpendicular to the adopted measuring profile, and in the vertical direction). The measuring profile and the arrangement of the probes are shown schematically in Figure 1. The source of vibrations was a vibro hammer type ICE 28 RF.

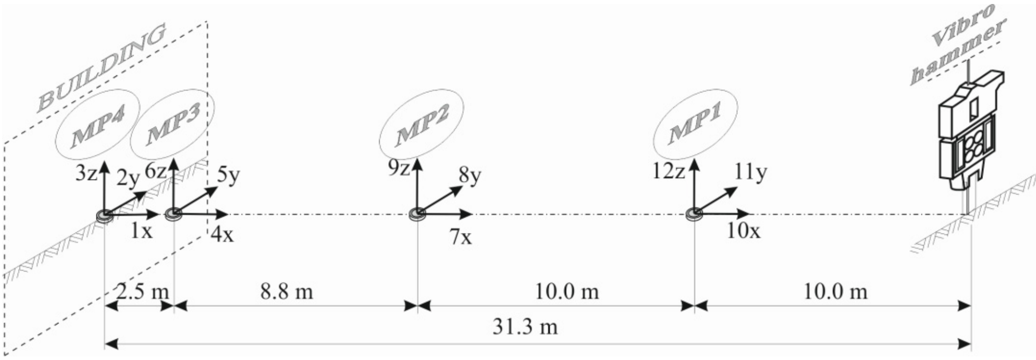

Figure 1: The measuring profile with numbering of measuring directions and sensors

3 Measuring Instruments and Research Methodology

A measurement system used to register vibration accelerations was a 24-bit LAN-XI by Brüel&Kjær, with the dynamic input levels of 160 dB. Other devices used in the test were: a set of eight low-frequency, seismic, piezoelectric transducers of vibration acceleration type 8340, made by Brüel&Kjær (with a sensitivity of 10 V/g and measurement range of ±0.5 g in the frequency range from 0.1 Hz to 1500 Hz), a set of four accelerometers type 3191, manufactured by Dytran (of sensitivity of 5 V/g and measuring range of ±1.0 g – in the frequency range from 0.1 Hz to 1000 Hz).

Figure 2: A view of measurement points (MP1 and MP2) with attached seismic sensors

In the course of measurements seismic sensors of vibration acceleration were fixed to mounting bases secured in the ground by a three-point anchor (measuring points 1 to 3). Mounting bases used in the test were in the shape of a ring. Three-point anchoring ensured improved connection of the bases and the ground than in case of anchoring with a single point (e.g. heads with a single pin (Maciag et al. 2005)), or the measurement carried out by means of sensors positioned directly on the ground. In the case of the fourth measurement point (MP4) seismic acceleration sensors were rigidly bolted to the load-bearing wall of the building at the level of the surrounding area facing the source of vibration.

Dytran sensors type 3191 were installed vertically in the first measurement point (MP1) – closest to the source of vibration (at a distance of 10.0 m from the source of vibration), in which it was expected to record maximum amplitudes of acceleration, and in the second measurement point – MP2 (located at a distance of 20.0 m from the source of vibration). 8340-type sensors by Brüel&Kjær were placed in the other measuring points (MP3 and MP4) and in a horizontal plane of the second point (MP2). Bases and sensors used in the field tests are shown in Figure 2.

4 Tests Results

Waveforms recording of acceleration of vibrations generated and propagated to the environment during the vibratory pulling out of sheet piles was carried out simultaneously (without phase shift) using all twelve of the sensors in each case oriented in three mutually perpendicular directions (x, y, z), and deployed in the four measuring points. The registration of vibration acceleration was conducted with a frequency of 4096 samples per second with activated high-pass filtering of signals with a cut-off frequency of 0.1 Hz ±10%.

Vibratory extraction of individual sheet piles lasted at least several minutes. The initial measurements at the adopted sampling frequency of 4096 samples/s resulted in very large and difficult to process digital data files. Therefore, it was finally decided to register 60- and 120-second vibration acceleration waveforms. As a result of this assumption, more than one waveform was registered for each sheet pile (except for the last analysed sheet pile, in which case only one file was registered).

Vibrations recorded during the procedure of pulling out the next four sheet piles (Nos. 1 to 4) are shown in Table 1 in terms of the peak particle acceleration (PPA) – separately for each of the analysed direction of measurement and adopted points in the ground (MP1-MP3) and the load-bearing wall of the building (MP4).

Name of file (time [s])	Peak particle acceleration (separately for each direction: x, y, z) [mm/s^2]											
	L_1 = 10.0 m (MP1)			L_2 = 20.0 m (MP2)			L_3 = 28.8 m (MP3)			L_4 = 31.3 m (MP4)		
	x	y	z	x	y	z	x	y	z	x	y	z
1-1 (60)	561	495	511	603	619	366	345	429	296	119	43	66
1-2 (60)	501	468	343	444	483	394	445	424	258	85	39	64
1-3 (60)	443	433	190	413	370	388	391	393	243	78	50	58
1-4 (60)	447	369	392	421	369	390	312	375	196	65	34	44
1B-1 (60)	696	531	668	675	635	478	263	633	193	91	71	39
1B-2 (60)	426	383	356	442	362	233	223	502	132	49	30	28
2-1 (60)	341	341	325	418	369	392	205	444	208	56	40	60
2-2 (60)	250	215	202	271	170	146	126	353	172	34	29	32
3-1 (120)	390	303	440	338	316	321	220	418	105	50	36	27
3-2 (120)	52	42	51	280	129	189	108	132	79	22	30	16
4-1 (120)	283	266	361	-	-	-	237	308	133	42	32	23

Table 1: Summary of vibration accelerations

After the analysis of the data summarised in Table 1 and in Figure 3 to Figure 5, it becomes apparent that the most intense of surface vibrations propagated in the ground are generated during the initial phase of extraction of individual sheet piles (files: 1.1, 1B-1, 2-1, 3-1). Each subsequent accelerogram has a much smaller amplitude values compared to the first recorded file (files: 1-2, 1-3, 1-4, etc.).

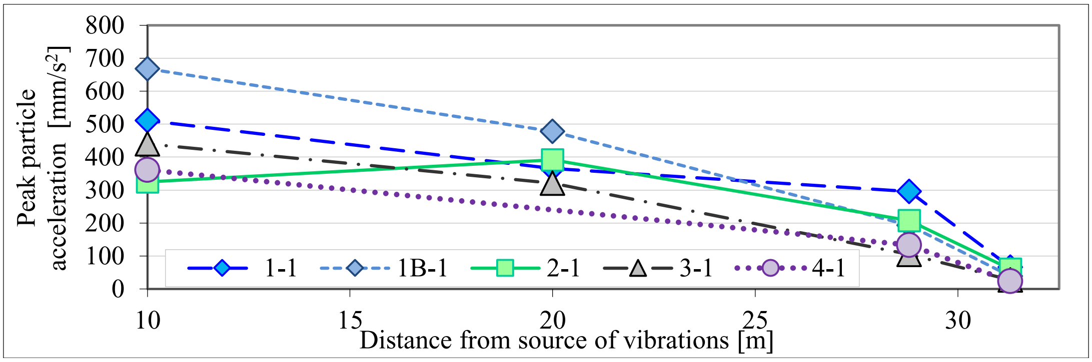

Figure 3: Comparison of vibration accelerations propagated towards the z-axis

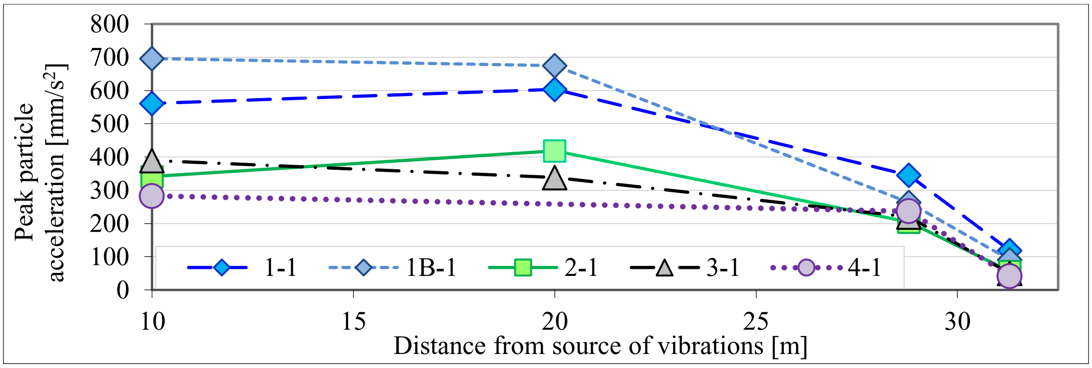

Figure 4: Comparison of vibration accelerations propagated towards the x-axis (in the radial direction)

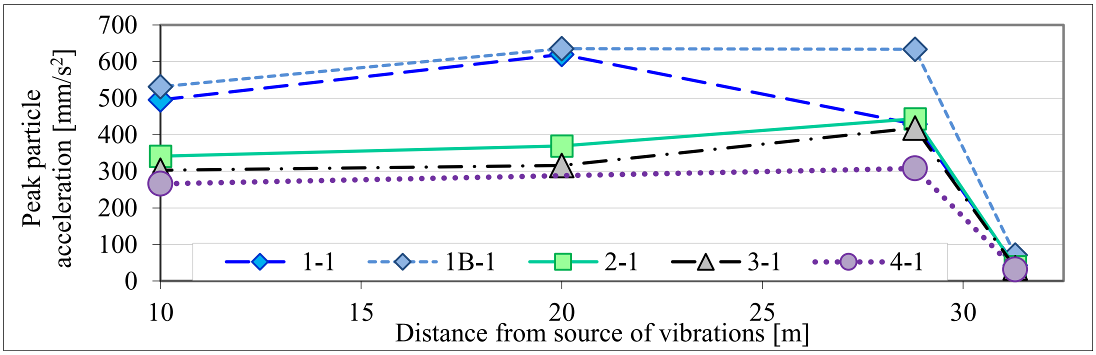

Figure 5: Comparison of vibration accelerations propagated towards the y-axis

If we compare with each other distributions of amplitudes only relating to the first (most important) of the recorded vibration acceleration waveforms in individual measurement directions (Figure 3 to Figure 5) it will be evident that vibrations towards the vertical z-axis are the fastest to damp (Figure 3). In this case, the curves indicate virtually linear fading of amplitudes of the vibration acceleration with increasing distance from the source of vibration. In the case of vibrations propagated in the horizontal plane we are dealing with a completely different course of absorbing and damping vibrations in the ground. As shown in Figure 4, amplitudes of the waves propagated in the direction of the adopted measurement profile (x – in the radial direction), practically do not change in value between the 1st and 2nd measurement point. A significant reduction in vibration in MP3 (the third measurement point) can be observed only after waves pass another ten meters. In the case of vibrations propagated in the horizontal plane in the direction perpendicular to the adopted measurement profile (Figure 5), virtually continuous slow increase of the amplitude of vibration acceleration recorded in the ground can be observed. In each of the above cases it was observed that the amplitudes of vibration acceleration at the junction of ground and foundation of the building were significantly reduced (i.e. dynamic interaction). In the present case, there was at least several-fold reduction of vibration amplitude – especially in the case of vibrations propagated in the direction perpendicular to the adopted measuring profile (y), wherein at least an 89% reduction of vibration amplitude was confirmed, as compared to amplitudes recorded in MP3 (file: 4-1).

By analysing the above graphs showing the rate of vibrations fading with distance due to damping and absorbing of them in the ground, it can noticed that the results of research conducted by the authors significantly differ from theoretical dependence of the geometrical attenuation and absorption of vibrations as in continuous and homogeneous types of ground (Hao, H. et al., 2001), which points to the exponential nature of fading of vibrations along with distance traversed by the waves:

$$A_r = A_0 \sqrt{\frac{r_0}{r}} \exp\left[-\alpha\left(r - r_0\right)\right] \text{ [mm/s}^2\text{]} \quad (1)$$

where:

A_r – peak acceleration attenuation of the recorded motions in the "r" point [mm/s^2],

A_0 – peak ground acceleration value [mm/s^2] at a distance r_0 [mm/s^2],

r and r_0 – distances of points "r" and "0" respectively, from the source of vibration [m],

α – coefficient related to material damping [1/m].

5 Effect of Vibrations on Buildings

Assessment of the impact of vibrations propagated through ground to neighbouring buildings can be carried out in an accurate manner (e.g. using MES) or in an approximate way. Due to vast labour consumption associating accurate methods the assessment of the effect of subsoil-propagated vibrations on buildings is typically carried out in an approximate method using the so-called dynamic impact analysis (SWD – in Polish) according to Polish Standard PN-85/B-02170. Unfortunately, not all buildings can be assessed based on approximate analysis of dynamic impact (SWD). The standard (PN-85/B-02170) only allows the use of SWD scales "in the case of masonry buildings (i.e. built with the elements laid and joined manually) and buildings constructed with large blocks". In the present case, the assessment was conducted on a four-storey, brick building with converted attic, which was eligible for evaluation by the use of less rigorous scale – SWD-II (buildings no higher than 5 stories, whose height is less than twice the minimum width of the building (PN-85/B-02170).

The assessment of potential harmfulness of vibrations propagated through the ground to the building was in compliance with the Standard PN-85/B-02170 and the Guideline 348/98 (1998), and performed for the vibration acceleration waveforms recorded on a load-bearing wall of the building facing the vibration source and at the level of the surrounding terrain. Waveforms of vibration accelerations registered in the course of the measurement were octave-analysed (1/3-octave range) in the frequency band from 0.5 Hz to 100 Hz, and the resulting data were plotted with boundary lines separating each section of hazard scale in SWD II. The most intense of the designated octave distributions for x and y directions is shown in Figure 6.

A nomogram (Figure 6) shows that in the case of the most detrimental waveform of vibration accelerations (file: 1-1), at a midband frequency 20 Hz for horizontal vibrations propagated in a direction perpendicular to the building (along the adopted measurement profile) the values obtained in the measurement were slightly lower than the limit values (line A – the lower limit of perceptibility of vibrations by the building and the lower limit of the dynamic impact consideration), beyond which the vibrations would have to be qualified as the second class of damage – i.e. vibrations perceptible through the building, but otherwise harmless for the structure (according to Polish Standard PN-85/B-02170). Further assessments conducted for the data recorded in minor intervals for the same sheet piles, demonstrated significantly less intense octave distributions.

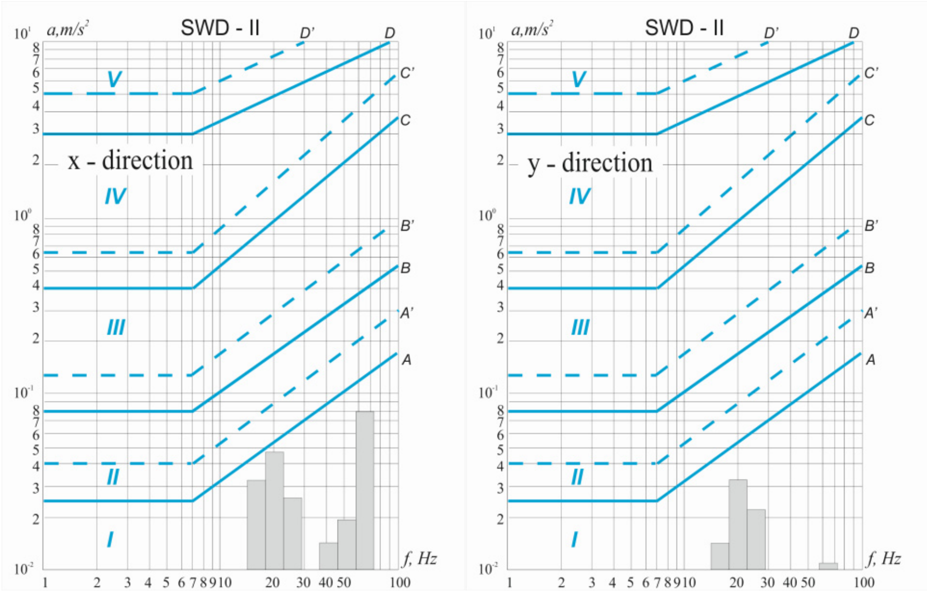

Figure 6: The assessment of harmfulness of vibrations propagated through ground to analysed building (file: 1-1)

According to Ciesielski et al. (1993) in forecasting the impact of vibrations on buildings "assuming vibrations in the foundation as identical to vibrations of the subsoil is the most commonly used approximation on the side of certainty". The above assumption is of course a major simplification because it omits the impact of dynamic interaction associated with a reduction in vibration amplitudes and lowpass filtering of the signal, which occurs at the interface of ground and a building (Maciag, 2006). However, such an assumption enables performing an approximate forecast assessment of occurring vibrations on hypothetical building, if it was located closer to the existing source of vibration, in this case, the vibro hammer. The analysis of assessments of vibration impact, carried out on this basis and recorded in the ground in the first, second and third measurement points (respectively MP1, MP2 and MP3) indicates that in the worst possible case (with no reduction in the level of vibration of measurement points set in the ground), the vibrations occurring then, would have to be classified, in accordance with the Polish Standard PN-85/B-02170 as the second and even third vibration hazard class.

The intensity of the vibration propagated during the removal of sheet pile elements can also be expressed by amplitude values recorded in the horizontal plane of the ground at the measuring points MP1-MP3 (Table 1). In any of the above points recorded values exceeded 0.005 g. In the case of a newly designed building, in accordance with the Polish Standard PN-85/B-02170, it would be necessary, as early as at the design stage, to take into account the impact of additional dynamic loads on the structure of the building.

6 Conclusions

The problem of the negative impact of vibrations generated during the vibratory driving of sheet piles is generally known in engineering practice. In this study, as the authors wish to indicate, pulling out elements of sheet pile wall with the use of vibro hammers is often a source of vibration level comparable and, in some cases, even higher than the level of vibrations generated during the process of driving sheet piles into the ground. This fact is often underestimated and can lead to unexpected structural damages. This study does not confirm any apparent harmful effects of vibration generated during the vibratory pulling of sheet piles on nearby commercial-residential buildings. It has been shown, however, that closer location of the vibration source in relation to the researched object can have a detrimental effect on the building, which according to the Polish Standard PN-85/B-02170, should be categorised as the second vibration hazard class.

The conducted study manifestly prove the necessity of monitoring the vibrations of nearby buildings during vibratory removal of sheet piles, particularly in the early stages of geoengineering works, which are accompanied by vibrations of considerable intensity. The supervising conducted for both insertion and pulling of the sheet piles closest to the adjacent building may enable timely response to excessive vibration levels recorded at the measuring points located on buildings. Such action directly translates into minimising the potential damages to buildings or it completely eliminates them. Vibration measurements conducted in the initial stage of this type of geoengineering works may also help set working parameters of vibro hammer which are safe for both the buildings and the users, and which can, after the monitoring, be used in driving and pulling out the sheet pile walls positioned further away from the building.

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