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Vibration monitoring as a method for assessing the pile driving-induced impact in restrained urban conditions

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Abstract. Vibration can cause damage to the building structure, reducing its operational reliability: reducing stability, impairing the load-bearing capacity of slabs and also causing cracks. To prevent the above causes, the vibration loads acting both on the structure as a whole and on its parts should be monitored. This paper discusses the results of a measurement of vibration caused by pile driving in soil and an adjacent housing complex. The aim of the study was to determine the minimum permissible distance from the pile-driving site at which neighbouring buildings would remain unaffected. For the measurements, control points installed at unequal distances from the pile driving location and directly on the building were used to allow observation of the pattern of vibration changes. It is preferable to select vibration measuring points directly on the structure to assess the impact of vibration on the structure. It is recommended that the measurement points are on the side of the structure facing the source of vibration. The actual vibrations in terms of speed, amplitude, acceleration and frequency were recorded during the measurement process. On the basis of the resulting vibration characteristics, damping (absorption) coefficients were determined and the maximum permissible pile-driving distance was then calculated. Measurements of building vibration are carried out in order to compare the results obtained with the specified limit values.

1 Introduction

With many high-rise construction projects, pile foundations are a standard structural solution [1]. In addition to standard static tests, dynamic tests, and continuity tests, vibration monitoring has become a widespread practice [2].

As a method evaluating the impact of piling, vibration monitoring is gaining wider use also with high-density development projects [3]. Different standards regulate different criteria for evaluating the vibration impact. For example, the German standard classifies pile driving as safe if the vibration rate does not exceed 5 m/s. According to the requirements of Industry-Specific Construction Standards (ISCS), which are applicable in the post-Soviet territory, the permissible pile driving-induced vibration acceleration should not exceed 0.15 m/s2 [4, 5]. Similarly, there exist different theoretical methods for calculating maximum permissible distancing of pile driving sites (which are applied at the preliminary feasibility

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stage). These methods use as criteria the background data on the structural features of the building or structure adjacent to the pile driving site; the engineering and geological descriptions of construction site; and specifications of pile-driving equipment [6-8]. That said, the ISCS prescribe the minimum permissible pile driving distance of 25 m.

In our study, the vibration monitoring, the purpose of which was to determine the maximum permissible distancing of the pile driving site based on soil vibration measurements, covered two apartment complexes adjacent to the construction site (Fig. 1). The design minimum distancing of the piling field from the two adjacent apartment complexes is 35-40 m. The two adjacent apartment complexes are 12-storey reinforced-concrete structural frameworks with gas concrete block walls.

Fig. 1. Site layout.

2 Methods

The vibration monitoring process involved the following stages:

1. theoretical, preliminary calculation of the allowable distancing of the pile driving site, based on ISCS method;
2. experimental measurements of the pile driving-induced vibration impact on adjacent buildings (based on several reference measurements and the assumption that the pile driving site is at the closest distance from the apartment complex under study);
3. experimental measurements of the pile driving-induced vibration impact on the foundation soil (based on unequally distant reference points);
4. follow-up calculation of the allowed distancing of the pile driving site, based on the obtained vibration monitoring data.

The background data for the preliminary calculations included the type of pile and installation method; the distance between the pile driving and the building; hammer specifications; characteristics of the foundation soil in the area of measurement; building specifications; the building condition category; and the building foundation type.

The preliminary calculations involved automated computations based on ISCS method [9, 10]. The target parameters were coefficients λ and δ. Coefficient λ characterizes the ratio of the maximum vibration acceleration in the soil near the pile driving site to the maximum permissible vibration acceleration in the foundation, taking into account the transmission of the soil vibrations to the foundation [11-13]. In this case, the transmission of the soil vibrations by the foundation is determined by a coefficient characterized by the ratio of the foundation vibrations amplitude to the amplitude in the soil near the pile driving site. Coefficient δ characterizes the change in vibration parameters with an increase in the distance from the pile driving site (soil vibration damping coefficient or vibration absorption

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coefficient). This coefficient is calculated using Bouguer's law, which describes the attenuation of parallel monochromatic light beam as it travels in an absorbing medium:

$$I(l) = I_0 e^{-k_\lambda x}, \tag{1}$$

where $I(l)$ is, in our case, the vibration that has travelled a certain distance in the ground; I_0 is vibration in the ground near the source of excitation; e – base of the natural logarithm equaling 2,718; k_λ is, in our case, δ, is absorption of vibration by the ground; x is distance between the excitation source and the building (or any other point relative to which vibration attenuation is measured.

The vibration monitoring involved two stages [14]. The first stage involved measuring the vibration in the soil with distance from the source of excitation. The second stage measured the vibration in building as pile driving was in process. Based on the results from the first stage, an assessment was made of the potential impact of pile driving process and the vibration absorption capacity of the soil. Based on the results from the second stage, we calculated the vibration impact on the building and, ultimately, the maximum permissible distancing of the pile driving site.

Conditions observed in the first stage: worst case scenario, when the pile driving site is at the closest distance from the building under monitoring; number of measurements minimum but sufficient to obtain reliable results (consistent with the number of piles being driven); minimized distortion of vibration measurement in the soil associated with installation of sensors. Sensors were installed on the buildings (priority measurements) taking into account the following factors: foundation structure; load-bearing structures being rigidly adjacent to the foundation; presence of load-bearing structures that are connected with the foundation through one (two) intermediate structures of rigid abutment; etc. For the purpose of vibration measurements in the soil, we made use of a massive portable slab heavy enough to allow it to resist the shock-vibration effects and the surface vibrations in the ground. The sensor installation locations are shown in Figure 2.

Fig. 2. Vibration monitoring sensors.

3 Results

3.1 Preliminary theoretical calculations

To calculate the maximum allowed distancing of the pile driving site from the adjacent building, we determined δ and λ:

$$\delta = \frac{\sum \delta_i d_i}{l} = 0.086 \quad (2)$$

where δi = attenuation coefficient for i-layer of soil along the length of the pile: 0.1 (stiff loam, d=3.5 m); 0.07 (water-saturated sand, d=l-3.5 m);

di = thickness of for i-layer of soil within the length of the pile, m;

l = length of installed pile (6.6 m);

$$\lambda = \frac{a_1}{k \cdot 4\pi^2 A_0 f^2} = 0.011 \quad (3)$$

where a1 = allowed acceleration in the foundation: 0.15 m/s2 (Category 3 soils);

k = coefficient of soil-to-foundation vibration transmission: 0,6 according to clay loam fluidity performance;

A_0 = vibration amplitude in the soil at a distance of 0.5 m from pile driving site: 2.9 mm (soil density: stiff, semi-solid loam); and

f = vibration frequency at the above distance: 14 Hz.

The theoretically obtained value of the maximum allowed distancing of the pile driving site exceeds 25 m (Fig. 3). The reason may lie in the presence of semi-solid loam, whose oscillation frequency measures 14 Hz.

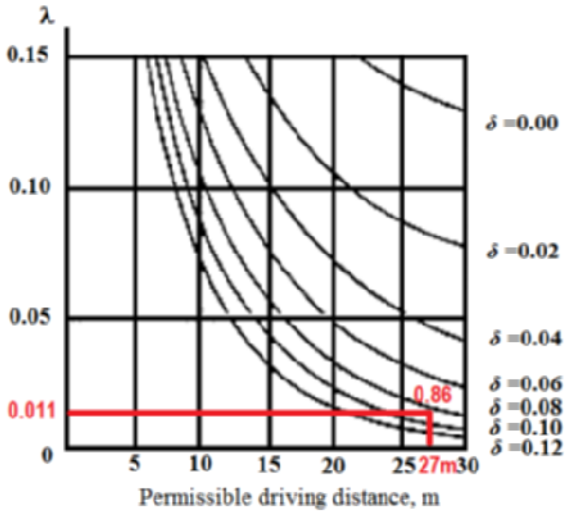

Fig. 3. Allowed distancing diagram.

3.2 Vibration monitoring results

Table 1 shows the statistical data of vibration measurements.

Table 1. Vibration measurement parameters.

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	Acceleration, m/s^2	Velocity, m/s	Frequency, Hz	Amplitude, mm
0.5 m	1.66	123.5	21.8	9.434
5.0 m	0.58	44.1	16.4	3.362
15.0 m	0.19	14.2	22.1	1.112
40.0 m	0.08	1.2	35.3	0.011
Building	0.04	0.5	52.9	0.007

According to the data obtained, all the parameters except frequency, have an inverse proportionality with distance from the excitation source. The direct proportionality of the frequency change is explained by the fact that the frequency of self-induced vibration in the building, which equals 52.89 Hz (maximum), as well as the self-induced frequency in the ground, which equals 35.34 Hz (pile driving-induced impact is absent at a distance of 40 m, as is shown by the statistical data given below), exceeds the pile driving-induced frequency of the vibration in the soil, which equals upon approximation 21.76 Hz (maximum). All other self-induced vibration values are lower than the pile driving-induced ones.

The charts in Figures 4-7 show the pile driving-induced vibration performance (ordinate-the driving indicator) relative to self-induced vibration (abscissa). The resulting ratios, particularly linear equation coefficients, will indicate the degree of deviation in the variables under comparison relative to each other. The greater the deviation of the coefficient from 1, the lower the convergence of the values compared, the greater the vibration effect from the pile driving process on the measurement point.

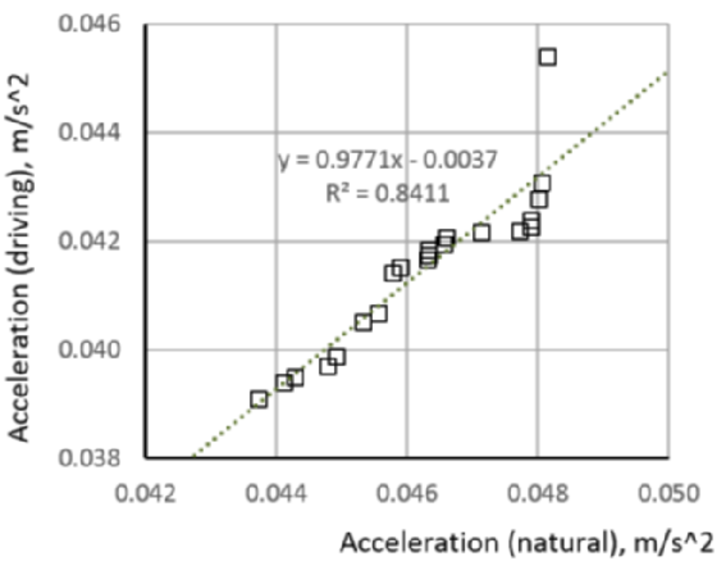

Fig. 4. Accelerations comparison.

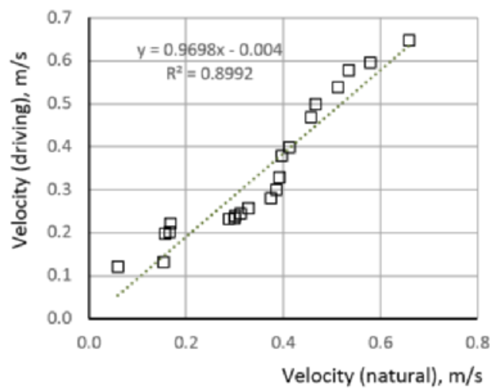

Fig. 5. Velocity comparison.

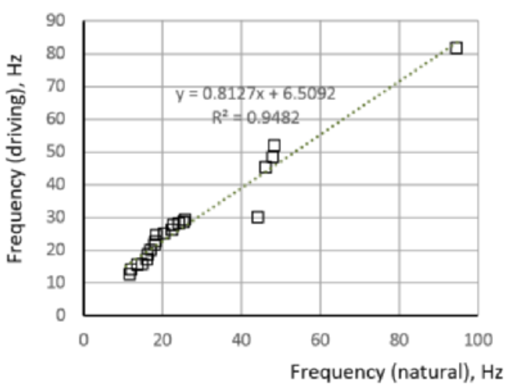

Fig. 6. Frequency comparison.

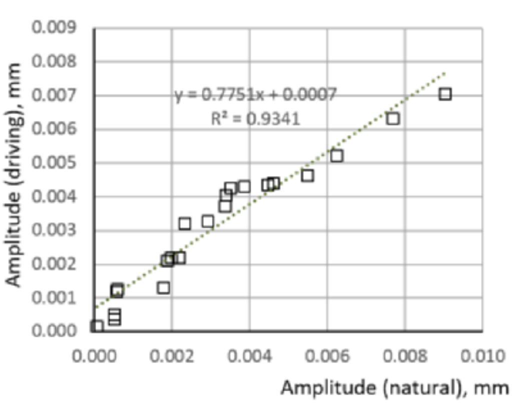

Fig. 7. Amplitude comparison.

Similarly, the convergence analysis was carried out by comparing the statistical data on self-induced vibration against pile driving-induced vibration (Tables 2-5). The evaluation criteria in the Table: a is correlation coefficient $\left(\frac{Self-induced}{Pile\ driving-induced}\right)$; b is linear dependence coefficient.

Table 2. Statistical data.

Parameter	Reference points, m				
	Building	0.5	5.0	15.0	40.0
Acceleration					
a	0.917	0.904	0.557	0.688	0.629
b	0.977	27.7	0.813	0.741	1.65
Frequency					
a	0.974	0.858	0.986	0.910	0.522
b	0.969	149.5	6.75	1.48	0.881
Velocity					
a	0.948	0.790	0.740	0.634	0.823
b	0.813	0.775	0.365	0.435	0.198
Amplitude					
a	0.966	0.425	0.748	0.529	0.621
b	0.775	15.37	20.12	2.05	0.629

According to the obtained linear dependence coefficients (Table 2), the pile driving process does not cause any changes in vibration in the building; all the data elements are closely interrelated (i.e. fall within same ranges).

Further, as shown by the linear dependence coefficients, the pile driving process has a significant effect on the velocity, acceleration and amplitude of the vibration in the soil. As to the frequency, the impact it experiences is minor, as is the impact of the pile driving process on the frequency of self-induced vibrations. The effect of the pile driving process on the increase in the vibration velocity in the soil is found to decrease with distance, being zero at a distance of 40.0 m from the source. At the same time, the impact of of the pile driving process on the frequency of self-induced vibrations is found to be significant within 5.0 m from the source and negligent at a 15.0 m distance, decreasing with the distance. The same pattern is observed in amplitude: at a distance of 40.0 m from the source, the impact on the amplitude of self-induced vibrations of the soil is zero.

According to the statistical data (Table 2), a large degree of convergence of particular values is observed at reference point “Apartment Complex” (Table 2), which indicates the least influence of pile driving-induced vibration on the building's self-vibration (zero impact). The variability (discrepancy) of the statistical data on soil vibration at a distance of 0.5 m, 5.0 m and 15.0 m is indicative of the impact on the soils’ self-induced vibration performance. The statistical data for all vibration indicators at a distance of 40.0 m from the source, except for frequency, shows that the pile driving-induced impact on the soil’s self-induced vibration is zero. The reason why frequency constitutes an exception is mentioned earlier and lies in the inverse proportionality of frequency change relative to distance from the source, which, in turn, is explained by the high frequency of self-induced vibration.

3.3 Calculation of allowed distancing based on vibration monitoring results

For the purpose of calculating the maximum allowable distancing of the pile driving site, auxiliary coefficients δ and λ were determined based on the maximum values of the actual vibration parameters measured in the building and its surrounding soil:

$$\delta = \frac{ln\left(\frac{A_0}{A_i}\sqrt{\frac{l_0}{l_i}}\right)}{l_i - l_0} = 0.105 \quad (4)$$

where Ao = measured maximum amplitude of soil vibration at distance l0 = 0,5 m from pile driving site (source-induced vibration): 9.4 mm;

Ai =measured maximum vibration amplitude in the soil around building, at distance li = 40 м from pile driving site: 0.017 mm.

$$\lambda = \frac{a_1}{\frac{A_f}{A_i}a_0} = 0.135 \quad (3)$$

where a1 = allowable acceleration in the foundation: 0.15 m/s2 (Category 3 soils);

k = coefficient of soil-to- foundation vibration transmission; k equals Af/Ai;

Ai = measured maximum vibration amplitude in the soil near the building, at 40 m from pile driving site: 0.017 mm;

A_f = measured maximum vibration amplitude in the foundation, induced by the pile driving process: 0.009 mm; and

a_0 = measured maximum acceleration in the soil near the building, at a distance of 0.5 m from the pile driving site: 2.1 m/s2.

Figure 8 shows the potentially allowable distancing of the pile driving site, based on the vibration performance measured at different distances from the excitation source. Our analysis has shown that maximum allowable distance is rather an individual measure and depends on the distance at which the measurements are made (with account of nonlinear attenuation of vibration amplitude in soil relative to distance from the excitation source, as evidenced by variability of coefficient δ). As can be seen from Figure 8, the attenuation of vibration amplitude begins at 11-12 m from the excitation source.

Fig. 8. Allowable distancing of the pile driving site.

In our case, given the fixed layout of the buildings adjacent to the pile driving site, the maximum allowable distancing is 8 m. However, with any decreased distance of the pile driving site (the ISCS-prescribed standard of 25 m is exceeded), the results of the vibration monitoring appear invalid. This may be due to the variability in wave propagation conditions in the soil, or due to altered susceptibility of the building to vibration performance.

4 Conclusions

The vibration monitoring to measure maximum allowed distancing of the pile driving site have been performed in restrained urban conditions. Vibration has been measured at various distances from the excitation source. The measurements produced the data for calculating particular parameters of the vibration in the soil and in the buildings.

All the obtained values have a high convergence, decreasing with distance from the source, except for frequency (which is due to the high frequency of the soil's self-induced vibration). The statistical analysis has shown that a larger degree of convergence of particular values is observed at reference point near the building, which indicates the pile driving-induced vibration having the least possible impact on the building's self-induced vibrations, while the variability in soil vibration data for distances 0.5 m, 5.0 m and 15.0 m is indicative of the pile driving-induced vibration having an impact the on the self-induced vibrations of the soil.

The resulting maximum allowed pile driving distancing of 8 m is valid if piles are driven at the (minimum) distance, at which the measurements were made, i.e. 40 m from the building. Pile driving at a closer distance requires repeated measurement of the vibration performance and, consequently, adjusting of the maximum allowed distance as the soil conditions and vibration propagation near the building will be different.

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