Investigation of ground and foundation vibrations of an existing building during impact pile driving

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Abstract. Pile driving technology remains the most common in Arkhangelsk where the presence of soft soils is an engineering-geological feature. New construction is mainly carried out in the conditions of existing urban development. During pile driving dynamic effects that propagate in the ground can have a negative impact on existing buildings. In common conditions, a distance of more than 25 m is considered safe. Sometimes driving piles by hammer is safe for neighboring buildings at a shorter distance. Often such buildings have pile foundations. The monitoring of pile driving by diesel hammer was carried out at one of the sites in Arkhangelsk. Vertical vibration velocities were measured by a vibration analyzer with independent channels. One vibration sensor was installed on the ground surface, the other one on the foundation of a 5-storey building. Continuous recordings of vibrations allowed a detailed analysis of the driving process of each pile. The level of dynamic effects propagating in the ground changed with the penetration of the driven pile. The highest values were observed when pile foots passed through a layer of glacial deposits. Change in soil resistance to pile driving also affected the operation of diesel hammer. The level of dynamic effects increased as the distance to the driven pile decreased both on the ground surface and on the foundation of the building, while the values on the ground surface were higher. The ratio of the highest vertical peak vibration velocities on the ground surface and on the building foundation was determined by field studies.

1. Introduction

Geotechnical conditions of Arkhangelsk are difficult due to the presence of soft layers such as peat or silt [1] and in most cases the impact method is still used for driving piles.

Brick and reinforced concrete buildings continue to replace old wooden apartment buildings built in the middle of the last century. New buildings are located next to them as well as to typical 5- and 9-storey buildings of the Soviet period construction.

Pile driving by hammer causes vibrations that can have a negative effect on existing buildings. A distance of more than 25 m is considered safe [2]. As practice shows, pile driving by hammer is acceptable for neighboring buildings at a shorter distance [3-6]. Often such buildings have pile foundations. In this case, the level of vibration of the ground and foundation of the building will be different. According to VSN 490-87 [7], ratio of amplitudes of foundation displacements to amplitudes of ground displacement during vibrations is in the range 0.5-1.0, the specific value depends
on the number of stores and the foundation soil. Unfortunately, the type and parameters of the foundation of the existing building are not taken into account.

2. Materials and methods
This paper presents experimental data on determining the values of peak vibration velocities of the ground and pile foundation of a building that occur during impact pile driving on a construction site with typical geotechnical conditions for Arkhangelsk. The stratification of soils and their properties are shown in table 1.

Table 1. Geotechnical conditions of the building site.

| №  | Soil*          | h m   | \( \rho \) g/cm³ | W % | E MPa | \( \phi \) ° | c kPa | I_F % | PI % | I_L % | LL % |
|----|----------------|-------|------------------|-----|-------|-------------|-------|-------|------|-------|------|
| (1) | Filled soil    | 0.7...1.4 |  |  |  |  |  |  |  |  |  |
| (2) | Peat           | 1.7...4.0 | 1.01 | 372.0 | 0.3 |  |  |  |  |  |  |
| (3) | Lean clay (CL) | 0.6...1.1 | 1.94 | 30.1 | 8.0 | 16 | 16 | 11.5 | 20.0 | 0.57 | 43.6 |
| (4) | Lean clay (CL) | 5.9...9.5 | 2.13 | 17.5 | 20.0 | 23 | 34 | 7.8 | 10.8 | 0.23 | 26.5 |
| (5) | Lean clay (CL) | 0.8...3.6 | 2.01 | 22.0 | 16.0 | 18 | 24 | 7.6 | 10.9 | 0.72 | 27.4 |
| (6) | Lean clay (CL) | 0.6...5.1 | 2.13 | 17.5 | 20.0 | 23 | 34 | 7.8 | 10.8 | 0.23 | 26.5 |
| (7) | Lean clay (CL) | 2.4...7.2 | 2.08 | 20.1 | 26.0 | 24 | 34 | 11.5 | 19.2 | -0.16 | 41.1 |
| (8) | Lean clay (CL) | >5.7 | 2.08 | 21.6 | 20.0 | 22 | 34 | 9.5 | 15.4 | 0.18 | 35.5 |

* Soil formations from the pit bottom are shown in figure 2.a

A pit with a depth of 2.5-3.5 m was excavated for foundation work of the 12-storey section of a residential building. Part of the peat layer remained at the base of the pit, and fine sand (1’) 0.5 m thick was filled at the pit bottom to allow construction machinery to work. Diesel hammer DD-35 with hammer striking mass 3.5 t and maximum impact energy 89.6 kJ was used for pile driving. Precast-concrete sectional piles 17 m long (bottom section 9 m, top section 8 m) with a cross section of 0.35×0.35 m were driven to the depth of 16.8 m.

A typical 5-storey brick building on the project 1-300-2m (figure 1. a), with plan dimension of 54.0×14.16 m is located next to the building site. This building has a pile foundation. Reinforced concrete piles 9.0 m long with a cross section of 0.30×0.30 m are spaced at intervals of 1.0-1.1 m. Pile foots are located in lean clay (4) of glacial deposits.

The nearest row of piles to the building is at a distance of 8.7 m. According to Russian building codes [2], if the distance from the nearest driving piles less than 25 m, the allowable safe distance is taken based on the condition that the vertical velocity of foundation vibrations does not exceed the maximum allowable value for building taking into account its design features, engineering status and base soil. For this building, the maximum allowable values of the foundation vibration velocity are 20 mm/s [2], 10.8 mm/s [8], [9]. The prediction of the velocity of ground and foundation vibrations was calculated according to VSN 490-87 [7]. The calculation takes into account the type and state of the most solid layer of soil lying up to a depth of 6-8 m from the pit bottom, the mass of the hammer striking part and the number of storeys of the existing building. For a 5-storey building the allowable velocity of foundation vibration of 20.0 and 10.8 mm/s occurs when driving piles with diesel hammer DD-35 at a distance of less than 1.2 and 3.5 m, respectively.

Vertical peak velocities of ground and building vibrations were measured with vibration analyzer Vibran-3 with the vibration velocity range 0.1...500 mm/s, the frequency range 2...100 Hz, the sampling frequency 256 Hz. The vibration sensor 1 is located on the ground surface at a distance of 0.5 m from the building wall, the vibration sensor 2 on the protruding base plate at the level of the brickwork base (figure 1. b). Let us assume that the vibrations of the building at this location will correspond to the vibrations of the building foundation. This assumption is possible because measurements were made on the lower part of the outside bearing wall of the building, at a height of...
no more than 1 m above grade [8]. It should be noted that the measurements were made on April 03, 2020, and the ground near the building at the location of the vibration sensor installation was thawed.

![Figure 1. a – view of the building site; b – the location of vibration sensors.](image)

To obtain the dependence of ground and building foundation vibrations on the depth position of the pile foot position from the impact during driving the number of blows for every 0.5 m, and for the last meter – for every 0.1 m were counted. Vertical velocities of ground and foundation vibration were measured during driving of four piles located at different distances approximately on the same line perpendicular to the wall of the building. First the most distant pile was driven, gradually approaching the existing building. All bottom pile sections were driven before the top sections.

3. Results

The piles moved without impact to a depth of about 1.0 m under their own weight and the weight of the diesel hammer. Stable operation of the diesel hammer began only with a depth of 2.0-3.0 m. Driving the bottom pile sections to a depth of 8.3 m required 94-112 blows of the diesel hammer; the total number of blows for driving the piles to a depth of 16.8 m is 481-732. Changes in driving resistance influenced the operation of diesel hammer. Increase of the resistance resulted in rising of striking part of diesel hammer, thus increasing the time between successive hammer impacts $\Delta t$ (figure 2.b).

Vertical vibration velocities of the building foundation when driving the bottom pile sections did not exceed 2.0 mm/s, which is less than 10.8 mm/s, so it was decided to drive the top sections. The peak vibration velocities at the beginning of driving the top sections of the pile were higher than the peak vibration velocities recorded at the end of driving the lower sections (figure 2. c). On the ground surface this difference was 45-77%, on the foundation of the building 15-78%. An increase in the level of propagating dynamic effects during a break in pile driving is associated with the restoration of the structure of clay soil [10]. When driving four piles, the break after the end of driving the bottom sections and the beginning of driving the corresponding top sections was 1.5-2.0 hours. The increase in vibrational velocities of the ground and building foundation can probably be explained by the fact that the foot of the piles could be at the border of layers (5) and (6).

The intensity of propagating ground vibrations induced by pile driving depends on the penetration of the driven pile. The highest values were observed on the ground and on the building foundation when the pile feet passed through lean clay (6) of glacial deposits (figure 2.c).

The level of dynamic effects decreases as the distance from the driving pile increases, both on the ground surface and on the building foundation (figure 3). For the distances considered in this paper, the highest peak vibration velocities of the building foundation were 2.0-2.1 times lower than the highest peak vibration velocities of the ground surface near the building. A similar ratio only for the
acceleration of ground vibration and building vibration at the first storey level was obtained for a 9-story brick building in the paper [11]. In figure 3, a dashed line shows the dependence of the ground vibration velocities on the distance from the driving pile, as determined by VSN 490-87 [7]. In this particular case, the obtained level of dynamic effects on the ground surface is very well consistent with the predicted level determined by the calculation.

**Figure 2.** a – soil conditions; b – relation of the time between successive impact of the diesel hammer on the penetration of the driven pile; c – relation of the vertical peak velocity on the penetration of the driven pile.

**Figure 3.** Graphics of the dependence vertical peak velocities on the distance from the driving piles vibration velocities on the distance from the driving pile, as determined by VSN 490-87 [7]. In this particular case, the obtained level of dynamic effects on the ground surface is very well consistent with the predicted level determined by the calculation.
4. Discussion
As a result of field measurements, it was found that the vertical peak vibration velocities of the building foundation did not exceed the allowable values. The velocity of foundation vibrations was less than the velocity of ground surface vibrations, which is due to the load of 5 storeys, structural stiffness of the building and the fact that pile foots are restrained in a reliable clay soil.

A good agreement between the obtained and calculated values of the ground vibration velocities shows that the predicted level of dynamic effects is possible according to the method of VSN 490-87 [7] for building sites with similar geotechnical conditions and when driving piles with rod diesel hammers. Coefficient of 0.5 should be used to get the vibration velocity of the pile foundation of a 5-storey building. According to the VSN 490-87 [7] for this building and ground conditions this coefficient is 0.9, the difference can be explained by the fact that the type and parameters of the foundation of the existing building are not taken into account.

5. Summary
For buildings on pile foundations which are based on reliable clay soils the dynamic effects caused by pile driving are lower than on the ground surface. For a 5-storey building, the ratio of the highest peak vibration velocities of the pile foundation to the ground surface vibrations can be taken as 0.5 on average.

Based on the results presented in this work in the future the numerical modeling of dynamic effects in the soil during pile driving to study the vibration of buildings of different storeys, influence of pile spacing and pile length of this building and other parameters can be conducted.

6. References
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