Impact of Dismantled Sheet Pile Vibration on Cohesive Soil Parameters

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Abstract. The dynamic impact of geotechnical works can affect subsoil, as well as structures and technical devices. In order to prevent hazards resulting from vibration, the monitoring of geotechnical works execution is necessary. This paper presents an analysis of the relationship between the vibration caused by pulling out the sheet pile and the variability of cohesive soil parameters. The authors present the case study of a construction site in Wrocław (Lower Silesian Province, Poland). The sheet pile profiles were used as a temporary protection of the foundation excavation. After the underground floors were constructed, the sheet piles were pulled out from the ground using vibrating techniques. This is a typical action to recover steel profiles that can be reused. While the sheet piles were being pulled out, the cohesive soil adhered to steel surfaces. In order to analyse the impact of dismantled sheet pile vibration on the variability of soil parameters, laboratory tests of basic soil physical and mechanical properties were carried out. The results were then compared with the primary parameters of soil as specified in the geotechnical documentation, which had been made at the initial stage to determine the geotechnical conditions for the foundation of the designed building. The comparison has shown a negative effect of vibrations on soil properties, including a decrease in the strength parameters, as well as an increase in the liquidity index and compressibility. In this case, an increase in the earth pressure on the existing underground structures and a reduction of the bearing capacity of shallow foundations may occur. Therefore, the vibration monitoring during sheet pile dismantling process is also very important.

1. Introduction

They are many kinds of ground vibrations existing in nature, caused by earthquakes, traffic loads, machinery, engineering works, wind power, and so forth. In practical geotechnical engineering, many problems are caused by the response of soil subjected to the vibrations.

Attempts to measure the influence of geotechnical works on existing infrastructure have been reported in the course of large pile driving, infrastructural projects and tunnelling works [1,2]. Structural damage caused by vibrations can be limited by the use of construction and connections resistant to excitation based on passive, active or semi-active techniques of vibration reduction [3] and the use of barriers in the ground to prevent surface wave energy transfer [4,5].
To analyse the response of subsoil subjected to dynamic loads, the shear modulus and damping properties are required. Shear modulus is affected by various factors such as strain amplitude and overconsolidation ratio. The reduction of the shear modulus under strain has been observed since 1970. However, other geotechnical parameters influenced by vibrations are also very important for calculating the earth pressure on the retaining structure, foundation walls and the adjacent shallow foundations [6].

Steel sheet piles are applied mainly to provide temporary or permanent protection of deep excavations against the groundwater inflow as well as to protect the stability of excavation walls. Temporary sheet pile walls are expensive and it is uneconomical to leave them in the ground as they can be reused as excavation protection. One of the commonly used methods for installing or extracting piles and sheet piles is vibratory driving [7, 8]. However, vibrations have a negative impact on the environment, especially on the subsoil. In the past, many researchers and civil engineers were concerned about the variability of soil parameters under cyclic load in drained and undrained conditions. Reduction of geotechnical parameters may cause exceeding the limit states for soil and structures [9-13].

In general, the process of vibration transfer is divided into three parts [12]:

1. Source of vibrations:
   a. Energy transfer between hammer and pile,
   b. Vibration in sheet piles,
   c. Interaction between pile and soil.

2. Wave propagation in soil.

3. Structure affected by vibration:
   a. Interaction between soil and structure,
   b. Vibration transmission in structures.

Furthermore, during the sheet pile vibratory driving, three types of resistance occur: soil resistance under the pile base, resistance on the side surface and sheet pile friction in the lock. While pulling out, the pile friction in the lock increases, but soil resistance under the pile base does not occur. Pulling out steel profiles requires overcoming strength in profile locks and friction forces on the surface sheet pile – soil [14]. Field tests were aimed at carrying out measurements of acceleration, velocity (horizontal, and vertical) at the sheet pile cup and obtaining soil samples affected by vibration. In practical cases, the accelerations (vertical and horizontal) are typically measured on the surface of structural elements. The measured amplitudes are then compared with values in the reference standard, which allows impact to be classified to specific risk groups of damaging structure [15-18]. However, it is also very important to control the influence of dynamic geotechnical works on the properties and behaviour of subsoil at all stages.

The purpose of this article is to analyse the effect of vibration caused by a dismantled sheet pile on the variability of cohesive soil parameters.

2. Research site and measurement conditions
The measurements were carried out in April 2018 in the western part of Wroclaw City (Lower Silesian Province) in Poland, as part of the “Legnicka Street II” project [19]. Field tests included measurements of vibrations propagating in the subsoil as a result of extracting sheet piles with use of a vibratory pile driver. Design of the excavation protection assumed sheet pile 16 m long, reaching to the layer of semi-compact clays, and recessed in them approximately 4.0 m deep. In this case, VL605 steel profiles were used to protect the excavation. Their geometrical and strength characteristics are presented in figure 1 and table 1.
Figure 1. Cross-section of VL605 sheet pile [19]

Table 1. VL605 Sheet pile parameters: a) single pile; b) per 1 m of wall [19]

|   | Width b [mm] | Height h [mm] | Thickness t [mm] | Thickness s [mm] | Weight [kg/m] |
|---|--------------|---------------|------------------|------------------|---------------|
| a) | 600          | 420           | 12.3             | 9.2              | 82.1          |

|   | Moment of inertia Iy [cm²/m] | Elastic section modulus Wy [cm³/m] | Cross sectional area [cm²/m] | Weight [kg/m²] | Coating area [m²/m] |
|---|------------------------------|----------------------------------|------------------------------|----------------|---------------------|
| b) | 42.433                       | 2021                             | 174.2                        | 136.8          | 2.91                |

The measurements were performed during engineering works that consisted in pulling out a sheet pile after completing the underground part of the building. Sheet piles were driven and dismantled with use of an ABI vibratory pile driver (figure 2).

Figure 2. Pulling out of sheet pile profile
This equipment is characterised by high vibration frequency (40 Hz) and maximum amplitude equal to 9 mm. The vibration pile driver worked on a large crawler machine (approximately 60 t). Its characteristic is presented in table 2.

### Table 2. Parameters of ABI vibratory pilling drive

| Parameter                              | Unit | Value  |
|----------------------------------------|------|--------|
| Overall height                         | mm   | 2720   |
| With                                   | mm   | 690    |
| Depth                                  | mm   | 1405   |
| Total weight (with clamp)              | kg   | 4140   |
| Static moment                          | kgm  | 0-20   |
| Dynamic mass                           | kg   | 2750   |
| Amplitude x 2                          | mm   | 15     |
| Nominal revolutions                    | min\(^{-1}\) | 2140 |
| Centrifugal force at nominal frequency | kN   | 1000   |
| Static extraction force max.           | kN   | 200    |
| Nominal oil pressure                   | MPa  | 32     |
| Hydraulic flow rate max.               | l/min| 769    |
| Required hydr. power at vibrator       | kW   | 400    |

3. Data acquisition and processing

The appropriate sensor location is a very important issue during the vibration monitoring of engineering structures. As the measured values in the form of three velocity components (three orthogonal directions x, y, and z) are compared to threshold values provided in special codes for vibration monitoring, it is crucial to locate sensors at points where the maximum soil/structure response can be observed [2].

![Graph](a)
The studied phenomenon was complex because the dynamic load of vibratory hammer applied to the head of one profile that is being pulled out causes the propagation of the wave to the steel profiles remaining in the soil and the surrounding soil. During the pulling out of the profile, its section remains in the ground and becomes shorter, causing propagation of the wave in the soil and adjacent profiles. The speed of propagation of longitudinal and transverse waves in steel is different from the speed of waves in the soil. In addition, along the temporary sheet piles, there is a solid reinforced concrete wall that causes wave reflections. Dynamic measurements were performed using Profound VIBRA+ equipment. The Profound geophone designed for the VIBRA range has 3 channels (x-, y-, and z- directions). Each accelerometer has a sensitivity of 23.3 Vs/m and mass of 11±0.5 g, and the velocity data save level is adjustable between 0.01-100 mm/s. Besides continuously monitoring the x-, y-, and z- directions, the VIBRA also automatically corrects the measurement data for individual sensitivity of each geophone channel.

Figure 3 shows the measured amplitudes in the form of velocity - time and acceleration-time graphs for point No.1 during the entire pulling process.

4. Geotechnical conditions
The original geotechnical parameters of subsoil were recognised and described in the geotechnical documentation prepared by a local geotechnical company at the initial stage of the project [20]. To determine the geotechnical conditions for the foundation of the designed building, field and laboratory tests of subsoil were performed. The layout of soil layers and selected parameters are presented in figure 4. The soil layer marked as IIb (clayey sand with liquidity index equal to 0.30) was subjected to a detailed analysis as cohesive soils sensitive to vibrations. While the sheet piles were being pulled out, samples of cohesive soil that adhered to steel surfaces were taken.
5. Laboratory tests

Laboratory tests were conducted on cohesive soil samples collected after pulling out the sheet pile. The basic soil properties, such as soil type and water content, were determined. Furthermore, the liquidity index and strength parameters were obtained.

As the soil parameters specified in the geotechnical documentation [20] were determined according to the Polish Standard [21], the comparative tests were carried out based on it as well. The grain size distribution was determined with use of hydrometer analysis. The liquidity index (LI) was obtained based on equation 1. For this purpose, the water content (W), plastic limit (PL), and liquid limit (LL) in Casagrande apparatus were analysed.

\[
LI = \frac{W - PL}{LL - PL} \quad (1)
\]

Furthermore, the strength parameters, such as cohesion (c) and internal friction angle (\(\phi\)) were determined. The test was conducted in a direct shear apparatus under normal stress 50, 100, 200, 300, 400 kPa and at a shear rate of 0.05 mm/min.

In addition, oedometric constrained modulus and oedometric modulus of deformation were obtained based on Polish Standard [22]. Also, the preliminary assessment of the microstructure of the analysed soil was carried out [23].
6. Results and discussion

The laboratory tests results of cohesive soil collected after extracting the sheet pile are presented below.

The results of soil granulometric composition are shown in figure 5 as a grain size distribution curve. Based on this, the type of soil was defined as clayey sand (clSa).

![Grain size distribution](image)

**Figure 5.** Grain size distribution

Based on stereoscopic microscope images (figure 6), it was determined that most of the grains are subrounded. In addition, they are characterised by cubic form and moderate roughness.

![Stereoscopic microscope image](image)

**Figure 6.** Stereoscopic microscope image
The values of natural water content, Atterberg limits and liquidity index are summarised in Table 3.

**Table 3.** Atterberg limits and liquidity index

| Type of soil | Water content W (%) | Plastic limit PL (%) | Liquid limit LL (%) | Liquidity index LI [-] |
|--------------|---------------------|----------------------|---------------------|------------------------|
| clSa         | 13.42               | 12.03                | 15.64               | 0.39                   |

The results of the strength parameters test are presented in Figure 7.

![Shear strength curve of the analysed soil](image)

**Figure 7.** Shear strength curve of the analysed soil

In order to analyse the effect of dismantled sheet pile vibration on the soil parameters, the obtained results were compared with the primary parameters of soil specified in the geotechnical documentation (Table 4).

**Table 4.** Comparison of cohesive soil parameters before and after the vibration process

| Vibration process | Liquidity index LI [-] | Cohesion c [kPa] | Internal friction angle φ [°] | Oedometric constrained modulus M₀ [kPa] | Oedometric modulus of deformation E₀ [kPa] |
|-------------------|------------------------|------------------|--------------------------------|----------------------------------------|------------------------------------------|
| Before            | 0.30                   | 22.00            | 19.50                          | 23500.00                               | 16500.00                                 |
| After             | 0.39                   | 18.15            | 17.49                          | 18500.00                               | 13500.00                                 |

The results have shown a negative effect of vibrations on the analysed soil properties. The liquidity index increased, and so did the plasticity of the soil. The strength parameters deteriorated, which in turn reduced the bearing capacity of the soil. Furthermore, the oedometric module values decreased significantly, which means that the compressibility of the soil increased.

This behaviour of cohesive soil may result from an increase in pore pressure caused by vibration. Due to the lack of rapid dissipation, the pore pressure leads to a reduction of the effective stress (which in turn causes reduction of soil strength) as well as to an increase in plasticity and deformation.
of soil [11]. This phenomenon has been indicated by Massarsch [13] as the cause of stability problems and slope failures. Furthermore, the reduction in strength parameters can increase earth pressure on retaining structures, foundation walls and adjacent shallow foundations [6]. Therefore, vibration monitoring is necessary both at the stage of driving and extracting of the sheet piles.

7. Conclusions

The presented research concerns vibrations during pulling out the sheet piles of the ground. Based on the performed research and analysis, the following conclusions were drawn:

1. The dismantling phase is also very important for the safety of structures and subsoil.
2. Vibration works have a negative impact on the geotechnical parameters of the soil. The cohesive soil plasticity and compressibility increased with the decrease in strength parameters.
3. Vibration monitoring is necessary not only in the initial phase of the sheet pile hammering but also in the process of dismantling.

Therefore, in some cases, to avoid the risk of vibration, it is reasonable to use static pulling out with a vibration-free hydraulic actuator.

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