Analysis of Displacements and Horizontal Load Capacity of Foundation Piles-Road Acoustical Barriers

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Abstract. The main objective of the study is the analysis of horizontal displacements of foundation pile heads used in the design of road barriers, limiting harmful noise emissions. As a part of the work, there were determined extreme values of the horizontal load capacity of piles, extreme values of horizontal displacement of the pile heads and displacement values for forcing horizontal test impacts. The research results, obtained in field tests, show that both horizontal displacement of pile heads from field tests and displacement values obtained as a result of the analytical calculations, according to PN, are considerably smaller than displacements in the extreme state of side load capacity of piles, as well as the permissible value, according to PN (10 mm).

1. Introduction
Noise is one of the major environmental health problems in the EU. Noise at the level of 35 to 70 dB causes tiredness and sleep problems in people’s lives. Exposure of the organism for a longer time to the noise level above 70 dB leads to damage of hearing and diseases, such as circulatory, nervous or hormonal systems. According to the World Health Organization (WHO), noise pollution occupies the second place after the air pollution on the list of environment-related factors causing the most diseases in Europe. The European Environment Commission, the World Health Organization, and the European Environment Agency address the problem of negative impact of road noise on human’s health and the environment [1, 2]. The European Environment Agency reports that the largest source of noise, causing exposure of noise of exceeding norms to the people, is the noise from road traffic. Directive 2002/49/WE relating to the assessment and management of noise in the environment is the most important legal instrument at EU level to protect citizens against excessive noise caused by road, rail and air traffic, as well as by large industrial plants [3, 4]. In Poland, the permissible noise level generated by traffic on roads and railway lines, depending on the type of terrain is between 50 and 65 dB during the day and by 10 dB lower in the night, respectively [5]. Limiting the impact of road noise on people and the environment can be implemented by planning technical solutions. Minimizing the negative effects of noise is possible by locating roads in places that are the least burdensome to the environment, and by installing acoustical barriers in the course of road routes. Proper reconnaissance of the construction site using GIS and remote sensing can enable the construction of roads, not only by
less damage of the natural environment and the surrounding, but also by avoiding geotechnical problems related to the complicated conditions of the construction substrate [6].

2. Research results and discussion

One of the modernization elements of the section of national road No. 4 was the construction of acoustical barriers. Required for their construction tests of static horizontal short loads (3.3 and 3.9 m in length) of reinforced concrete piles drilled with a continuous flight auger, constituting acoustical barrier supports, were carried out in autumn in 2009 and in spring 2010 [7]. In the surrounding of the planned investment, there are single-family housing of a farm, and commercial and garage character, as well as home gardens, copses, thickets and communal roads [8]. In order to protect single-family housing against excessive noise, three sections of acoustical barriers with a total length of 355 m were constructed in the structure absorbing and reflecting sound waves. Spacing of modular supports for barrier elements varies from 1.63 to 4.00 m, with the maximum spacing being for passage gates. The height of anti-noise barriers is 3.5 m. The modular barrier elements are mounted between steel I-beam pillars, positioned on reinforced concrete piles, formed in the ground using a continuous flight drill. For reflecting barriers, the pile penetration in the ground is 3.3 m and 3.9 m for barriers that absorb sound waves. The diameter of piles is 600 mm [9]. The geotechnical conditions of the investment area have been determined in the geotechnical documentation [10] on the basis of carried out field and laboratory tests. In the carried-out research, differentiated ground conditions were founded, thus two geotechnical zones were separated.

- In the first geotechnical zone, there was determined the occurrence of Holocene consolidated native soils [10] in the form of silty clays, sandy silts and silts. The degree of plasticity in the subsurface layer (to a maximum of 2.0 m depth below the surface area) was about 0.33 and below about 0.20 (the study was carried out to a depth of 5.0 m below the surface area).

- In the second geotechnical zone, there was found a building embankment which was made of sandy clay with traces of gravel up to a height of 2.6 m, deposited on a native substrate, made of silty clays, sandy silts and silts. The degree of plasticity of the embankment is about 0.20. The upper layer of the native substrate with a thickness of up to 3.1 m had the degree of plasticity about 0.33. In a deeper substrate, the degree of plasticity was about 0.20. These are anthropogenic and Holocene soils normally consolidated. The research in the second geotechnical zone was carried out to a depth of 9.0 m.

Testing research

Due to the occurrence of two types of foundation pile lengths in the foundation construction for testing in the horizontal direction, piles with the most unfavorable combination of forcing impacts were selected. In the first geotechnical zone, six piles with a length of 3.9 m were tested (for barriers absorbing sound waves) and four piles with a length of 3.3 m (for barriers reflecting sound waves). In the second geotechnical zone, one pile with a length of 3.9 m (for the barriers absorbing sound waves) and one pile of 3.3 m in length (for the barrier reflecting sound waves) were tested [7]. Measurements of horizontal displacement of test pile heads were carried out until the moment of stabilization of displacements (but not less than five minutes’ duration of a given load level). The piles were tested with a static horizontal action of four degrees of values, given in Table 1 [7].

Due to the different character and values obtained as a result of static tests of horizontal displacements of pile heads in two separate geotechnical zones of the ground substrate, they were analyzed separately. In the first geotechnical zone during the trial static tests, fast stabilization of the displacement of the pile heads was observed, which occurred within one minute from the beginning of the test. The values of horizontal displacements of test pile heads for 1.5-times size of the design useful impact of the piles did not exceed 0.25 mm (Figure 1) [7].
Table 1. Values of forcing horizontal impacts

| Lp. | Piles - length 3.3 m | Piles - length 3.9 m |
|-----|----------------------|----------------------|
| 1   | 0.75 x $H_{\text{max}}$ = 4.58 kN | 0.75 x $H_{\text{max}}$ = 6.46 kN |
| 2   | 1.00 x $H_{\text{max}}$ = 6.11 kN | 1.00 x $H_{\text{max}}$ = 8.61 kN |
| 3   | 1.25 x $H_{\text{max}}$ = 7.64 kN | 1.25 x $H_{\text{max}}$ = 10.76 kN |
| 4   | 1.50 x $H_{\text{max}}$ = 9.16 kN | 1.50 x $H_{\text{max}}$ = 12.92 kN |

Figure 1. The first geotechnical zone. Dependence of the horizontal displacement of the test pile heads on the duration of the test impact A) length of piles 3.3 m B) length of piles 3.9 m
In the second geotechnical zone, the stabilization of horizontal displacement of the test pile heads took place within four minutes from the moment of triggering the test impact. The values of horizontal displacement of test pile heads for the 1.5-times test size of the design useful impact of the piles did not exceed 3.00 mm (Figure 2) [7].

![Figure 2. The second geotechnical zone. Dependence of the horizontal displacement of test pile heads with a length of 3.3 m on the duration of the test impact A) length of piles 3.3 m B) length of piles 3.9 m](image)

2.1 Analytical calculations of the extreme load capacity and horizontal displacement of the pile heads

There were determined extreme values of the horizontal load capacities, and extreme values corresponding to test impacts of the horizontal pile heads. The calculations were made on the basis of analytical formulas from the Polish Standard [11]. Based on the PN formula [11]:

$$h_r = n + \sqrt{\frac{4EJ}{kxD}}h^n$$  

(1)
where:
hs - springy pile penetration in the ground,
n - power exponent equal to \( n = 1 \) for cohesive soils normally consolidated,
EJ - stiffness of the pile,
kx - side susceptibility soil factor,
D - dimension of the pile cross-section measured in the direction perpendicular to the horizontal force impact,
h - pile shaft penetration in the ground, the values of springy pile penetration in the first (\( hs = 4.3 \) m) and the second (\( hs = 4.5 \) m) geotechnical zone were determined.

Due to the stiffness criteria in the PN [11] (\( h < 1.5 \) \( hs \rightarrow h = 3.3 \) m \( < 1.5 \) \( hs = 6.4 \) m in the first geotechnical zone and \( h = 3.9 \) m \( < 1.5 \) \( hs = 6.7 \) m in the second geotechnical zone), it was found that due to the horizontal load capacity, the piles work in the ground as rigid. Based on formulas with PN [11]

\[
H_f = \gamma D h^2 N_q i_q S_q + cD h N_{q} i_{c} c S_{c}
\]  

where:
\( \gamma \) – bulk density of soil along the pile shafts,
c - cohesion of the soil along the pile shafts,
\( N_q, N_c \) – load capacity factors,
\( i_q, i_c \) - coefficients taking into account the height of the application of the forcing impact in relation to the ground level,
\( S_q, S_c \) - coefficients of the cross-section shape of piles,

\[
y_0 = \frac{4H(1+1.5\frac{h_{HI}}{h})}{Dh k_x}
\]  

where:
y_0 - horizontal displacement of the pile head,
H - horizontal forcing impact,
h_{HI} - the height of application of the forcing impact in relation to the ground level;

Extreme and characteristic values of the load capacity of horizontal piles, extreme values of the horizontal displacement of the pile heads, and displacement values for forcing horizontal test impact were determined. Derived analytical values of the above-mentioned quantities are summarized in the following table No. 2. According to analytical calculations, the displacement of the pile heads for computational useful impacts of noise barriers, is from 11 to 12% displacement of heads in the extreme state of the horizontal load capacity. The computational impact of acoustic barriers on the heads of piles is from 1.2 to 1.4% of the horizontal load capacity of piles.
Table 2. The extreme values of side load capacities of piles, extreme displacement of pile heads and displacement of pile heads for forcing test impacts

| Extreme side load capacities of piles [kN] | Extreme displacement of the pile heads [cm] | Displacement of the pile heads for test impacts [cm] |
|------------------------------------------|------------------------------------------|--------------------------------------------------|
|                                          |                                          | The first geotechnical zone                        |
|                                          |                                          | Piles - length 3,3 m                              |
|                                          |                                          | Piles - length 3,9 m                              |
|                                          |                                          | The second geotechnical zone                       |
|                                          |                                          | Piles - length 3,3 m                              |
|                                          |                                          | Piles - length 3,9 m                              |

For the first geotechnical zone:

- Piles - length 3,3 m:
  - H = 4,58 kN → y₀ = 0,08
  - H = 6,11 kN → y₀ = 0,11
  - H = 7,64 kN → y₀ = 0,13
  - H = 9,16 kN → y₀ = 0,16

- Piles - length 3,9 m:
  - H = 6,46 kN → y₀ = 0,09
  - H = 8,61 kN → y₀ = 0,12
  - H = 10,76 kN → y₀ = 0,16
  - H = 12,92 kN → y₀ = 0,19

For the second geotechnical zone:

- Piles - length 3,3 m:
  - H = 4,58 kN → y₀ = 0,07
  - H = 6,11 kN → y₀ = 0,10
  - H = 7,64 kN → y₀ = 0,13
  - H = 9,16 kN → y₀ = 0,15

- Piles - length 3,9 m:
  - H = 6,46 kN → y₀ = 0,09
  - H = 8,61 kN → y₀ = 0,12
  - H = 10,76 kN → y₀ = 0,15
  - H = 12,92 kN → y₀ = 0,18

3. Conclusions
The values of horizontal displacements of the pile heads obtained in the field tests for the first stage of the forcing impact were lesser (ranging from 0 to 56%) than the values determined by the analytical method according to PN [11]. For the other three stages of forcing impacts, the horizontal displacement of the pile heads from field tests were similar or higher (ranging from 100 to 208%) than analytical values, according to PN for the first geotechnical zone and were much higher (between 1200
and 2250%) than analytical values according to PN for the second geotechnical zone. According to analytical calculations, the displacements of the pile heads for design useful interactions of noise barriers, are from 11% to 12% displacement of heads in the limit state of the horizontal load capacity. The calculation impact of the acoustical barriers on the pile heads is from 1.2% to 1.4% of the extreme horizontal load capacity of piles. The horizontal displacements of the pile heads from field tests, as well as the displacement values obtained as a result of analytical calculations, according to PN [11], are considerably smaller than the displacements in the extreme state of the side load capacity of piles and the allowed value, according to PN (10 mm).

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