Analysis of horizontal pile displacement caused by pit excavation

R A Mangushev\textsuperscript{1,2,3} and D S Kolesnik\textsuperscript{2}

1 Russian Academy of Architecture and Construction Sciences (RAACS), Russia
2 Department of Geotechnics; Saint-Petersburg State University of Architecture and Civil Engineering, 5, Ulitsa Egorova, Saint-Petersburg, 190005, Russia
3 geotechnica@spbgasu.ru

Abstract. In the case of thick soft and unstructured soils, pit excavation causes 20–75\% of pile heads to have higher-than-normal horizontal displacements. The paper presents the results of statistical analysis for 9865 piles installed in pile fields at 17 construction sites in St. Petersburg, Perm, and Volgograd. We note that the distribution of frequencies of horizontal pile displacements follows a normal law. During the analysis, we identified the main factors affecting pile displacement: the time when a pile is in the slope, the properties of the cut soils, their tendency to softening, the excavation scheme, and the availability of pile head anchorage. The paper justifies the effectiveness of pit excavation in work zones of up to two meters deep with changes in the direction of machinery movement. We provide recommendations for raft design and analysis with account for possible displacement of pile heads.

1. Introduction
Most high-rise buildings in residential complexes are erected with well-developed substructures where parking lots and basements with utilities are located. These structures are usually based on piled raft foundations where the raft serves as a floor slab of the first floor.

Geological conditions of St. Petersburg are characterized by a thick layer of soft clay soils of glaciolacustrine genesis (lg\textsubscript{III}) in the upper part of the soil section. This complicates pile installation in the pit bottom since heavy construction machinery can get stuck or even tip over. Pit bottom stabilization with crushed rock or crushed bricks entails additional expenses, and it is not always possible to install vehicle ramps in restrained urban conditions.

The most common method is to sink prefabricated reinforced-concrete piles or install cast-in-situ piles, in particular, Fundex displacement piles, from the daylight surface \cite{1, 2}. A driven or jacked pile is sunk below the ground surface by 3–5 m using a pile follower. The Fundex pile head elevation usually matches the daylight surface level. During the second stage, the pit is shored and excavated using struts or soil berms with subsequent pile cut-off to the design level. In these cases, the pit depth varies from 5 to 8 m for structures with one or two basement floors.

During excavation, horizontal pressures caused by the difference in elevations (from the grade elevation to the pit bottom elevation) affect the piles. This factor is usually neglected. However, in the case of significant depths when pits are fully or partially excavated in soft underlying soils, pile heads show displacements that can be as large as several pile diameters and often exceed the permissible values (figure 1) \cite{3, 4, 5}. There are known cases of higher-than-normal displacements of a group of piles connected by a raft with the erection joint destroyed (figure 2), as well as cases of displacement of piles serving as temporary columns in structures built using the top-down method.
In St. Petersburg, this effect is observed both in the central (historical) part of the city and in large-scale residential complexes on the outskirts. Similar problems occur during construction in any region of the country, in particular, in Perm and Volgograd.

In accordance with the Russian Regulations SP 24.13330.2011, rafts are designed in such a way so that their edges overlap the edges of the pile group by 0.2–0.4 of the pile head size in the case of prefabricated piles and by 10 (15) cm in the case of piles with diameters of more than 500 mm. Such a margin is necessary to compensate for the manufacturing error in an individual pile. If the position of the heads in plan view exceeds these margins, the foundation structures have to be changed. In a number of cases, there is an issue related to the use of displaced piles.

Let us analyze the main factors affecting horizontal displacement of pile heads during excavation using a large number of findings of instrumental observations.

2. Methods

The majority of researchers exploring the subject note that most piles are displaced towards excavation [3, 4, 5, 6]. This can be confirmed with a dot plot for the actual position of 257 piles after excavation at one of the construction sites. The dots correspond to the actual position of the pile heads relative to their design position (0, 0). The documents confirm that the excavation works were carried out from left to right (against the X-axis direction).

The average pile displacements are as follows: 10 cm along the X axis; -3 cm along the Y axis (figure 3). Therefore, it is fair to say that the maximum pile head displacement will correspond to the axis, along which the specific pile field section was excavated.

To perform statistical analysis, we chose individual structural bodies / work zones where it was possible to determine pile displacement along one of the axes. In total, we analyzed 9865 piles with the heads displaced at 11 sites in St. Petersburg, one site in Perm, and another one in Volgograd.

Table 1 presents data on the percentage of piles that over the years had higher-than-normal displacements, as well as data on the pit depth and the excavation scheme in accordance with figure 4.
Figure 3. Dot plot for the actual position of the pile heads relative to their design position (0, 0).

Table 1. Main characteristics of the considered objects.

| No. | Year | Quantity of piles | Pit depth, m | Scheme | Publication |
|-----|------|-------------------|--------------|--------|-------------|
|     |      | All | 0.2d<≤0.4d | >0.4d |          |             |
| 1   | 2005 | 583 | 37% | 33% | 1.5 | a | [3] |
| 2   | 2012 | 279 | 31% | 55% | 4.8 | b | [3,5] |
| 3   | 2013 | 874 | 38% | 23% | 4.8 | b |        |
| 4   | 2014 | 1365 | 36% | 36% | 4.4 | b | [3,5] |
| 5   | 2014 | 1060 | 28% | 50% | 6.2 | b | [3,5] |
| 6   | 2016 | 399 | 23% | 68% | 5.4 | c |        |
| 7   | 2017 | 1301 | 32% | 51% | 6.7 | b | [3] |
| 8   | 2018 | 2369 | 35% | 41% | 4.4 | b |        |
| 9   | 2020 | 221 | 0% | 100% | 4.7 | d |        |
| 10  | 2020 | 117 | 46% | 15% | 1.8 | b |        |

|     | 10cm<≤15cm | >15cm |
|-----|-------------|-------|
| 11  | 506 | 14% | 75% | 5.4 | e | [4,5] |
| 12  | 296 | 14% | 65% | 5.7 | e |        |
| 13  | 494 | 28% | 38% | 4.8+4.7 | f |        |
Figure 4. Typical cases of pile displacement when piles deviate from their vertical position: a) due to a combination of pile jacking and pit excavation; b, e) due to pit excavation for the entire depth; c) due to soil defrosting; d) in the case of piles being a part of the raft; f) in the case of piles being a part of top-down structures; 1 — a pile driver; 2 — a prefabricated reinforced-concrete pile, 3 — defrosted soil, 4 — raft structures, 5 — a Fundex reinforced-concrete pile, 6 — reinforced-concrete slabs.
2.1. Description of shoring structures and pile field elements

In the soft soils of St. Petersburg, most pits are shored as they are excavated. The shoring is usually made out of steel sheet piling or, less often, using the wall-in-the-ground method [7].

Sites 1–10 (Table 1) used pre-fabricated reinforced-concrete piles of square section, with sides from 300 to 400 mm. Sites 11–13 used Fundex bored cast-in-situ piles with a shaft diameter of 520 mm. Table 2 shows data on the characteristics of the pile foundations and shoring. The daylight surface level is taken as the initial level.

**Table 2. Characteristics of piles and shoring.**

| No. | Quantity | Type       | Scheme          | Top of pile elevation, m | Pit depth, m | Shoring type               |
|-----|----------|------------|-----------------|--------------------------|--------------|---------------------------|
| 1   | 747      | S120.35    | Jacking         | -1.0                     | 1.5          | Unloaded slope            |
| 2   | 279      | S110.35    | Jacking         | -4.2                     | 4.8          | Unloaded slope            |
| 3   | 874      | S120.30    | Driving         | -4.5                     | 4.8          | Steel sheet piling        |
| 4   | 642      | S160.40    | Jacking         | -2.5                     | 4.4          | Steel sheet piling        |
| 4   | 723      | S150.40    | Jacking         | -3.5                     | 4.7          | Steel sheet piling        |
| 5.1 | 111      | S200.40    | Driving         | -4.3                     | 6.2          | Unloaded slope            |
| 5.2 | 110      | S220.40    | Driving         | -4.3                     | 5.2          | Unloaded slope            |
| 6   | 180      | S210.40+   | Driving         | -4.3                     | 5.4          | Figure 4c                 |
|     |          | S140(170).40 |                |                          |              |                           |
| 7.1 | 466      | S130.35    | Driving         | -5.2                     | 6.7          | Unloaded slope            |
| 7.2 | 735      | S180.40    | Driving         | -1.5                     | 3.2          | Unloaded slope            |
| 7.3 | 99       | S160.35    | Driving         | -1.5                     | 3.2          | Unloaded slope            |
| 8.1 | 254      | S150.40    | Jacking         | -3.7                     | 4.4          | Steel sheet piling        |
| 8.2 | 449      | S180.40    | Jacking         | -3.7                     | 4.4          | Steel sheet piling        |
| 9   | 221      | S170.40    | Jacking         | 0.0                      | 4.7          | Figure 4d                 |
| 10  | 117      | S160.40    | Jacking         | -1.5                     | 1.8          | Unloaded slope            |
| 11  | 72       | S2.157     | Fundex          | 0.0                      | 5.4          | Unloaded slope            |
| 12.1| 42       | S2.168     | Fundex          | 0.0                      | 5.7          | Steel sheet piling        |
| 12.1| 39       | S2.168     | Fundex          | 0.0                      | 2+2+1.7      | (additional displacements) |
| 12.1| 34       | S2.168     | Fundex          | 0.0                      | 2+2+1.7      | (additional piles)        |
| 12.2| 178      | S2.204+    | Fundex          | 0.0                      | 5.7          | Steel sheet piling        |
| 13  | 494      | S2.281     | Fundex          | 0.0                      | 4.8+4.7      | Reinforced-concrete wall  |
|     |          |            |                 |                          |              | in the ground             |

Note: S110.35 — a prefabricated reinforced-concrete displacement pile, square section (350 x 350 mm), length: 11 m (GOST 19804-2012); 157.52 — a reinforced-concrete bored Fundex displacement pile, circular section (d = 520 mm), length: 15.7 m.

For the entire sample, we determined frequencies of pile head displacements from the design position. In the case of prefabricated piles, the frequency series was based on displacements along the axis coinciding with the excavation front and the axis orthogonal to it. In the case of Fundex piles, displacement was evaluated using their absolute value.

We hypothesized that the frequency of pile displacement relative to the initial position has a normal distribution (Hₐ hypothesis). Then we tested the hypothesis by the chi-squared test at the significance level of 0.05. The sample mean was determined as follows:

$$\bar{x} = \frac{1}{n} \sum x_i n_i$$  \hspace{1cm} (1)
The sample standard deviation:

\[ \sigma = \sqrt{\frac{1}{n} \sum x_i^2 \cdot n_i} \]  

(2)

The chi-squared test value:

\[ \chi^2 = \sum \frac{(n_i - n')^2}{n_i} \]  

(3)

In equations (1), (2), (3): \( n \) — the sample size, \( x_i \) — the middle of the partial interval, \( n_i \) — the empirical frequency in the interval, \( n'_i \) — the theoretical frequency.

Let us note that, during the construction of large building complexes, neighboring work zones are often excavated with a difference in time up to several months, while piles are driven almost simultaneously. Therefore, a part of the pile field can be crossed by the slip lines of the slope whose stability in soft underlying soils is most often not ensured. In our study, we assessed this parameter as well.

3. Results

The results of the analysis expressly confirm that the frequencies of pile displacements at sites with more piles (sites 4, 7, 8, table 1) and at sites with FUNDEX piles (sites 11, 12, 13) have a normal distribution. For these samples, the diagrams plotted based on the theoretical and empirical data match, and the Ho hypothesis is adopted in accordance with the chi-squared test \( \chi^2 \). As an example, figure 5 shows pile displacements’ frequency distribution for one of the considered structural bodies in St. Petersburg.

![Figure 5](image)

**Figure 5.** Pile displacements’ frequency distribution for site 4: (a) along the excavation axis; (b) across the excavation axis. The solid line denotes empirical distribution, the dashed line denotes theoretical distribution, and the vertical line denotes the sample mean displacement.

Table 3 presents the study results in absolute and relative values. The \( d \) value means the width (diameter) of a pile. The pile fields excavated 2–4 months later than the neighboring ones are given in bold. The X axis runs against the direction of excavation, the Y axis is perpendicular to it (figure 3). The \( \bar{x} \) value denotes the sample mean deviation in the X axis, \( \sigma_x \) denotes the sample standard deviation, in a similar manner for the Y axis.

4. Discussion

During the analysis, we identified the following main parameters that can affect the final position of pile heads differing from their design position: the time when a pile is in the slope, the type and properties of the cut soil, the pit excavation scheme, the position of a pile foot with regard to firm soil
(ensuring anchoring against turning), and availability of horizontal anchorage of a pile head. The pit depth and the shoring stiffness have a lesser impact. The spacing of piles also has almost no impact on final horizontal displacements, and, in soft soils, the interaction between piles can be neglected when calculating such displacements.

Table 3. Resulting pile displacements.

| No. | Quantity | x, cm | σx, cm | y, cm | σy, cm | x, d | σx, d | y, d | σy, d |
|-----|----------|-------|---------|-------|---------|------|--------|------|--------|
| 1   | 747      | 9     | 12      | -1    | 9       | 0.3  | 0.4    | 0.0  | 0.3    |
| 2   | 279      | 7     | 14      | 7     | 16      | 0.2  | 0.4    | 0.2  | 0.5    |
| 3   | 874      | 3     | 8       | 1     | 8       | 0.1  | 0.3    | 0.0  | 0.3    |
| 4   | 642      | 6     | 16      | -1    | 13      | 0.1  | 0.4    | 0.0  | 0.3    |
| 5   | 723      | 5     | 16      | -1    | 12      | 0.1  | 0.4    | 0.0  | 0.3    |
| 5.1 | 111      | 6     | 10      | 0     | 8       | 0.1  | 0.2    | 0.0  | 0.2    |
| 5.2 | 110      | 19    | 13      | 0     | 13      | 0.5  | 0.3    | 0.0  | 0.3    |
| 6   | 180      | 31    | 24      | -28   | 33      | 0.8  | 0.6    | 0.7  | 0.8    |
| 7.1 | 466      | 5     | 13      | 1     | 12      | 0.1  | 0.4    | 0.0  | 0.4    |
| 7.2 | 735      | 17    | 16      | 0     | 13      | 0.4  | 0.4    | 0.0  | 0.3    |
| 7.3 | 99       | 35    | 26      | 5     | 11      | 0.9  | 0.6    | 0.1  | 0.3    |
| 8.1 | 254      | 5     | 15      | 7     | 9       | 0.1  | 0.4    | 0.2  | 0.2    |
| 8.2 | 449      | 22    | 11      | 0     | 11      | 0.6  | 0.3    | 0.0  | 0.3    |
| 9   | 221      | 18    | -       | -     | -       | 0.5  | -      | -    | -      |
| 10  | 117      | 4     | 9       | 1     | 9       | 0.1  | 0.2    | 0.0  | 0.2    |

Note that 95% of all pile displacement values are within the range of x ± 2 σx, and 68% are within the range of x ± 2 σx; the same goes for the Y axis.

4.1. Impact of time

According to table 3, the piles that for several months were in the zone of influence of earlier excavated pits are subject to the largest displacements. In this case, the displacements were caused by excavation and slope creep. Obviously, the piles uncovered by excavation were also subject to additional displacements before they were connected by the raft.

Note that border piles of the pile field were subject to maximum displacements, which could necessitate future changes in the geometry of the expansion joints of a building or entire complex.

As an example, figure 6 shows a dot plot of horizontal displacements of pile heads depending on their proximity to the pit slope (site 8, table 1). To obtain the resulting straight line, we used the method of least squares.

4.2. Impact of soil conditions

The analysis confirmed that the problem of pile displacement is peculiar to buildings that are erected on a thick layer of soft clay soils (table 1). At sites with compact sands and clay soils of firm consistency, the impact of pit excavation on pile field displacement can be neglected: piles are subject to the largest displacements in liquid clay soils with I_L = 1.1–1.3 (site 12.1) [8, 9] and in clay soils that have lost their structural strength. Soil destructuring can be caused by defrosting of the pit bottom and slopes (site 6), by piles being driven into thixotropic soils (site 7), and by watering of gypsiferous soils (site 10) [10].
Figure 6. a) Diagram showing the relationship between pile displacements and pile position relative to the slope (site 8); b) soil surface at the time of 8.1 work zone excavation.

4.3. Impact of the pit excavation scheme

As practical experience has shown, the pit depth (with excavation in a single work zone) does not have a significant impact on pile displacements. Furthermore, the assumed displacements can be significantly reduced by using a multi-layered excavation scheme. It is reasonable to set the depth of a layer within two meters.

For instance, at site 12.1 (table 1), initial pit excavation for the entire design depth caused pile displacement by 50 cm. After backfilling and installation of backup piles, the pit was excavated by layers, which reduced pile displacement in plan view by 60%. Table 3 provides values of additional horizontal displacements of the heads of existing piles and displacements of backup piles.

Note that the zero sample mean displacement of piles along the Y axis is peculiar to almost all sites. This is in good agreement with the standard excavation scheme (figure 7): some piles are excavated from the X; Y direction, and the rest are excavated from the X; -Y direction.
Therefore, it is expedient to change the excavation direction to the opposite one for each new excavation layer.

**Conclusion**

Based on construction experience and the analysis performed, we can make the following conclusions:

1. Piles are primarily displaced towards the pit. Both individual piles and piles being a part of rafts or entire structures can deviate from their vertical position.
2. Piles that have been in the near vicinity of a slope for 2–4 months are subject to additional displacements, which may exceed the displacements caused by excavation. The zone of pit influence on piles is about three depths of the pit.
3. The problem examined is relevant for construction sites with thick layers of soft soils or soils that have lost their structural strength. When piles are installed in compact sands and clay soils of firm consistency with subsequent excavation to a small depth (2–4 m), no horizontal displacements are observed.
4. The distribution of pile displacement frequencies follows a normal law. When the sample size grows, the convergence increases, and if there are more than 500 piles, it passes the chi-squared test with a confidence level of almost 100%.
5. The pile field, the raft structure, and the position of the expansion joints shall be designed with account for possible pile head displacement relative to the design position — by 1.5–2 diameters (width) rather than by 0.4 diameters (the value used in actual practice). Bearing this in mind, the pile stability shall also be calculated.
6. It is possible to reduce horizontal displacements of piles by excavating the pit in layers of a small depth, changing the direction of machinery movement to the opposite one when excavating each layer.

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