Geotechnical Engineering and Engineering Geology

SPECIFIC FEATURES OF THE CONSTRUCTION AND QUALITY CONTROL OF PILE FOUNDATIONS IN ENGINEERING AND GEOLOGICAL CONDITIONS OF SAINT PETERSBURG

Elizaveta Loseva[1]*, Anatoliy Osokin[2], Daniil Mironov[2], Ivan Dyakonov[2]

[1]Saint-Petersburg Mining University
21st Line, 2, St Petersburg, Russia

[2]Saint Petersburg State University of Architecture and Civil Engineering
Vtoraja Krasnoarmeyskaya st., 4, Saint Petersburg, Russia

*Corresponding author: elizaveta_loseva@mail.ru

Abstract

Introduction: The article reviews various methods of the construction and quality control of pile foundations in complex geological conditions of Saint Petersburg. The authors describe conditions, under which the geological structure of the city was formed. They list the main factors affecting the selection of foundation types and methods of their construction, describe soil properties influencing the quality of piles. **Methods:** Methods of pile construction based on different drilling technologies are presented (bored piles, pre-fabricated piles, displacement piles (with soil compaction and extraction)). Various methods of the quality control of piles constructed are also described (seismoacoustic, ultrasonic). **Conclusions:** Based on the results of the study, it is concluded that pile quality control methods shall be widely used and their applicability shall be extended. **Discussion:** It is suggested to improve methods of pile foundation integrity testing, increase their use on construction sites, study their applicability not only to detect defects in a pile but to control the quality of construction and materials used.

Keywords

Geology, foundations, pile technologies, control methods.

Introduction

Due to the specifics of their formation, the engineering and geological conditions of Saint Petersburg are rather complicated in geotechnical terms. They are characterized by a high stratification diversity, sandy and silty-clayed varieties alternating in depth, which contributes to their anisotropy in terms of water impermeability as well as physical and mechanical properties. A distinctive feature of the engineering and geological section in the historical districts of the city is the availability of thick soft soils represented by water-saturated silty-clayed varieties with organic inclusions. Due to their thixotropic properties, such soils can change their physical-and-mechanical, strength and deformation characteristics under the various dynamic or mechanical impact. Since morainic deposits are located at a depth of 16–18 m and lower, installation of pile foundations for new construction and foundation strengthening in historical buildings is a reliable and rational solution in terms of engineering.

One of the important criteria that determine the reliability of a pile foundation is the quality of works performed, conformance of the actual execution to the design. Among important qualitative parameters of pile construction, the following can be distinguished: the load-bearing capacity of a pile, pile penetration to the design depth (soil bearing layer), and integrity (continuity) of a pile body throughout its length. Such defects as caverns, voids, cracks, and significant splits in a pile body, or a pile toe failure to reach the design depth lead to the occurrence of non-uniform deformations, a decrease in the load-bearing capacity of the pile foundation, formation of cracks, or tilting, which is unacceptable. In construction, pile integrity and penetration depth are determined by seismoacoustic and ultrasonic methods. This review paper addresses and systematizes methods of non-destructive testing of different pile foundations constructed in soft water-saturated silty-clayed soils.

1. Engineering and geological conditions of Saint Petersburg

DOI: 10.23968/2500-0055-2020-5-2-38-45

In geological terms, soft soils are alluvial soils of different composition and origin that were not sufficiently consolidated under natural conditions. Such soils can be divided into three groups by their formation and occurrence: 1) lacustrine and marine deposits producing bedded formations (sands, sand clays, loams, clays, organic and mineral silts); 2) covering deposits (peats, clayey residual deposits of bed rocks, loess); 3) technogenic deposits. Soft soils are located almost all over the north-west areas, in particular, in Saint Petersburg, where landscape formation, stratification of soils, and their physical-and-mechanical properties are determined by the history of the geological evolution of the area in the Quaternary period (Dashko et al., 2011).

According to L. G. Zavarzin, the area of the city can be divided into three main soil complexes. The first one is mostly spread in the north of the city. It represents sands and light sand clays with relatively good structural properties, occurring from the surface to a considerable depth. The second one is mainly characteristic of the southern part of the city. It is distinguished by its favorable soil conditions represented by the Luga moraine occurring in the upper part of the natural bed. The third soil complex is associated with the formation of the Neva River and its delta, which resulted in the deposits of fine-grained and silty sands with a layer thickness of 2–5 m, underlain by a thick layer of soft lacustrine-and-glacial and marine deposits. Their thickness is usually within a range of 20–30 m. These deposits are represented by silty sands, sand clays, loams, and clays, layers of which may contain lenses and bands of peaty soils. Such soils are characterized by high natural moisture, porosity, high and non-uniform compressibility, heaving, and thixotropy (Mangushev and Osokin, 2010).

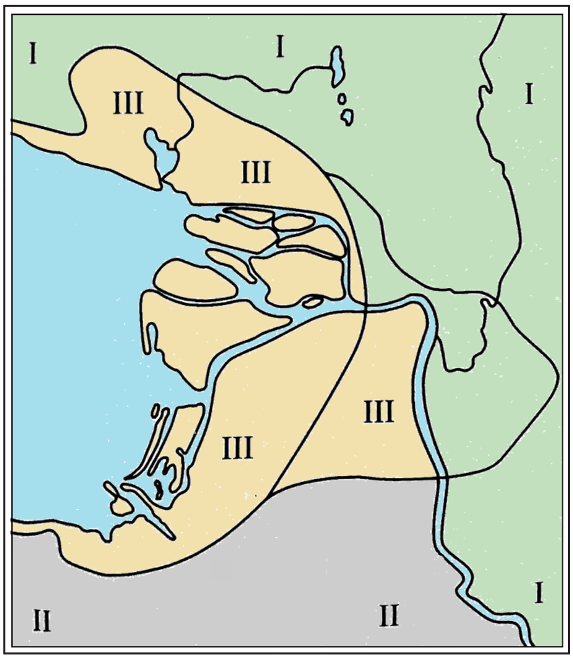


Figure 1. A map of the city area divided into soil complexes.

Then, there is a gradual transition from the mass of lacustrine-and-glacial deposits to the moraine top, occurring at depths of more than 10 m. It is this soil mass that is most often used for the implementation of construction projects in Saint Petersburg in terms of the construction of pile foundations for buildings and structures.

The primary deposits that occur in the lower part of the natural bed are characterized by a high degree of consolidation. In the southern part of the city, the structure of the upper stratum includes Lower Cambrian clays. Upper Kotlin clays are found under the Quaternary period stratum in the northern and central parts of Saint Petersburg, as well as under the Lower Cambrian clays in the southern part. These soil deposits are considered firm and serve as a confining layer.

2. Practical application of pile-construction technologies in Saint Petersburg

Modern construction uses various types of piles: pre-fabricated piles (driven piles inserted by pressing or vibration); cast-in-situ piles (bored, displacement, and drilled injection piles).

Currently, driven piles (Figure 2) are mainly used for residential and industrial construction in the peripheral areas of the city. As for residential and industrial construction, 25% of all pile works are performed with the use of driven piles.

a)

b)

Figure 2. Pile driving equipment (a) and types of defects in driven piles (b).

The main defects of driven piles in terms of integrity include cracks, splits, distortion of joints in sectional piles, and pile head destruction during installation.

In the built-up areas of the city, pile construction by jacking (by means of both Russian and imported equipment) is widely used (Figure 3). Piles are hydraulically gripped and jacked into the ground. By testing the integrity of such piles, we can determine defects occurring during installation (splits, cracks) and control the penetration depth when it is not possible to reach the design level due to stiff intermediate layers or solid inclusions.

Figure 3. Pile construction by jacking.

Today, displacement piles account for a significant share in the market of pile works (up to 45%). Such piles include piles made by the Fundex or DDS (Drilling Displacement System) technology. These two types of technologies differ in the method of pile construction. When the Fundex technology is used, a pile hole is made by rotating and pressing the “sacrificial drill bit – drill pipe” system to a given depth, then a cage is lowered through the open top of the pipe, and concreting is performed. Due to its particular advantages, this pile construction technology is in demand in Saint Petersburg. However, significant constructions risks and possible defects typical for the technology shall be noted: for instance, some authors (Mangushev et al., 2014) state that, during pile design studies, concrete-mixture stratification is observed, and in some soil conditions, the pile diameter reduces with the formation of necking (Figure 4b).

a)

b)

Figure 4. Pile construction using the Fundex technology (a) and a necking defect along the length of the pile shaft (b).

The DDS technology involves the excavation of a pile hole with a working tool without soil removal due to compaction. A drilling tool with a compaction system is lowered to the design level, then it is pulled back with the simultaneous pile-hole concreting, and after that, the pile hole is reinforced with a reinforcement cage. Among the disadvantages of the technology, changes in the pile shaft (formation of bulging) during concrete feeding under pressurization shall be noted, which leads to the excess consumption of concrete (Figure 5).

a)

b)

Figure 5. Pile construction using the DDS technology (a) and pile shaft bulging with the excess consumption of concrete (b).

The CFA (Continuous Flight Auger) method is another leading method among modern pile construction technologies (Figure 6). This technology is widely used in soils of different density and it is especially effective when penetrating thick strata of sand, semi-hard and stiff loams where it is not possible to use displacement piles. Pile hole concreting is performed using a concrete pump (concrete is fed through an inner tube of the working tool) with the auger being simultaneously removed. Immediately after the auger has been completely pulled out, a reinforcement cage is lowered into the concrete mixture. The CFA technology is distinguished by the following crucial aspect: auger flights have an active influence on the soil mass, which limits the use of the technology in soft soils where the deformation modulus is less than 5 MPa and the internal friction angle is less than 10°. Piles constructed by the CFA technology shall be tested for integrity.

Figure 6. Pile construction using the CFA technology.

DOI: 10.23968/2500-0055-2020-5-2-38-45

In geotechnical engineering and foundation engineering, the technology of pile drilling using a casing tube is considered a universal and traditional method, although it has a very small market share of 4%. This technology is used in the construction of foundations with a high load-bearing capacity, for bridge substructures, as well as for piles at significant depths over 40 m. The process of pile construction based on this technology consists in lowering a section casing pipe to the design level by progressive rotation. Then, the soil is extracted from the casing pipe using drilling tools (section by section), a reinforcement cage is installed, and concreting is carried out using the tremie pipe (vertically moving pipe) method. The technology has the following advantages: a reduced impact on foundation soils, which makes it possible to perform operations near the surrounding buildings; a wide range of piles in terms of size and depth. However, caverns and voids can generate in soft soils. Therefore, integrity testing is required.

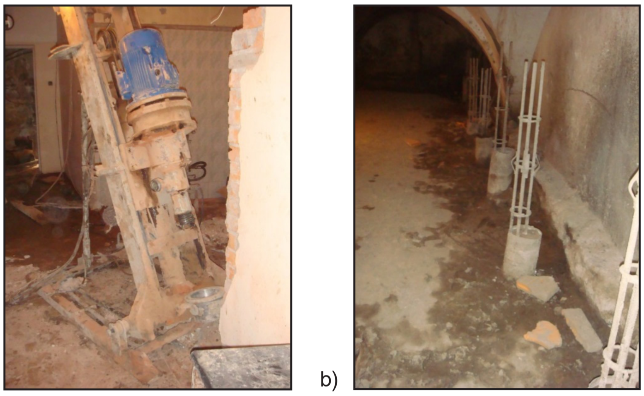
a)

b)

Figure 7. Pile construction with a casing pipe(a); a cavern in a drilled pile (b).

In Saint Petersburg, drilled injection piles are used to strengthen bases and foundations in the existing buildings and structures under reconstruction or restoration. Drilled injection piles can be constructed in the existing foundation, which makes it possible to transfer the load from the building to deeper layers of the soil body. To construct such piles, a pile hole is drilled by core drilling through the foundation and then through the soil body using slurry (by rotary drilling rigs) (Figure 8). After that, the pile hole is filled up with a cement mortar through a drill string. Immediately after cementing, a reinforcement cage is installed, which is lowered section by section. The sections are joined by welding.

a)



b)

Figure 8. Construction of drilled injection piles using a small drilling rig (a); heads of drilled injection piles used for underpinning (b).

It shall be noted that in soft soils, a small-diameter pile experiences significant bending moments and, therefore, strains. To control the reliability and quality of piles constructed, integrity testing shall be conducted. It is used to identify possible cracks and determine the actual diameter of bored piles.

3. Methods of pile integrity testing in soft soils

In the regulatory documents used in the 1990s, e.g. Construction Rules and Regulations SNiP 3.02.01-87 “Earthworks, grounds and footings” (Ministry of Construction, Housing and Utilities of the Russian Federation, 2017), the following parametric characteristics of in-process control were used to assess the quality of drilled piles: elevations of the top, bottom and enlargements; pile hole diameter; perpendicularity of the pile hole axis. For the piles constructed by the method of underwater concreting, pile integrity was determined as the absence of discontinuities in the pile shaft. Samples taken from drilled out cores or by other means were tested to check pile integrity. It was pointed out (Construction Rules and Regulations SNiP 3.02.01-87 “Earthworks, grounds and footings” Clause 11.28) (Ministry of Construction, Housing and Utilities of the Russian Federation, 2017) that, in order to determine shaft integrity in drilled piles constructed by the method of underwater concreting, samples taken from drilled-out cores should be tested randomly, or integrity should be checked using non-destructive methods. It also was noted that such tests should be applied once for every hundred piles but no less frequently than for two piles at the facility, as well as for all piles constructed with violations of the technology.

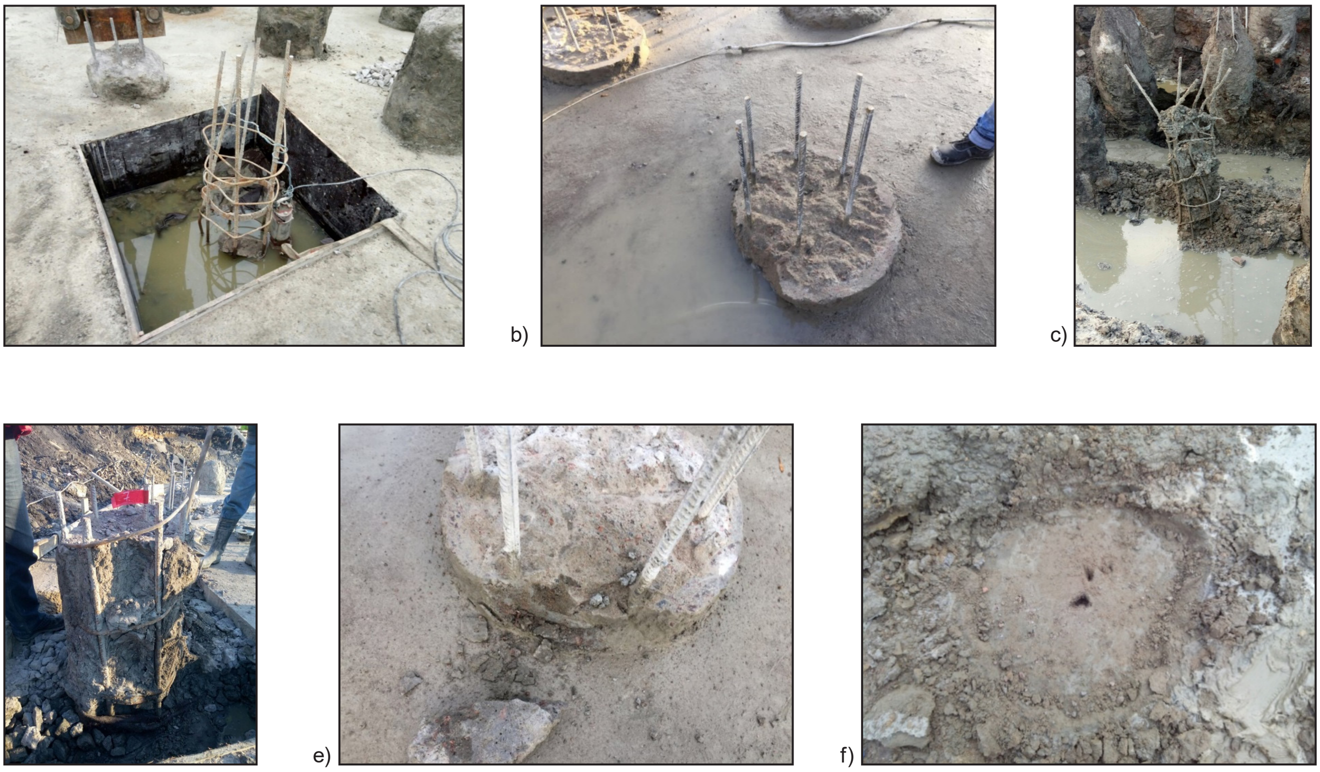
The applicable building regulations state that, during pile-foundation construction, it is required to perform total or random quality control depending on the objectives as well as the nature and degree of defects and damage. Total quality control includes the determination of integrity along the length by the seismoacoustic method and the evaluation of concrete homogeneity by the radioisotope or ultrasonic methods (Construction Rules and Regulations SNiP 3.02.01-87 “Earthworks, grounds and footings”, Clause 12.8.1) (Ministry of Construction, Housing and Utilities of the Russian Federation, 2017). Random quality control of pile concrete includes the following operations:

- drilling-out cores to the full length in the amount of 2% of the total number of piles made of cast-in-situ concrete on the site but no less than two piles; testing concrete samples made of the cores for uniaxial compression;

- controlling pile length and assessing pile integrity using seismoacoustic tests: 20% of the total number of piles on the site;

- assessing pile concrete quality (homogeneity) to the full length by means of radioisotope and ultrasonic measurements: 10% of the total number of piles on the site.

Let us demonstrate some defects that may occur in piles on a construction site (Figure 9):



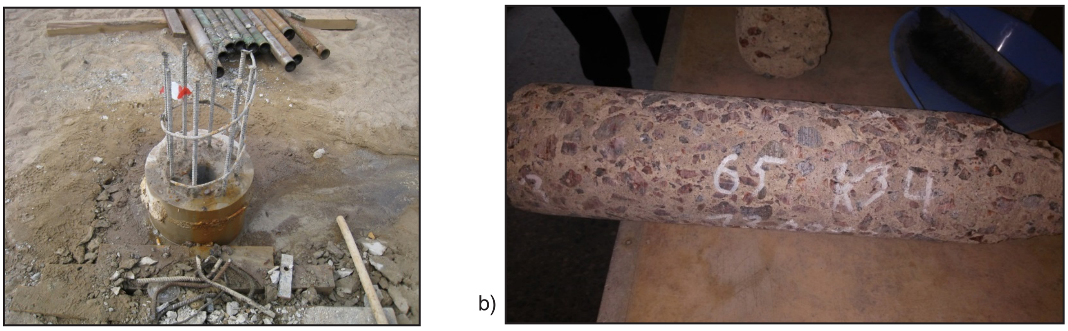
a) b) c) d) e) f)

Figure 9. Defects occurring in cast-in-situ piles: a) absence of concrete in a pile head; b) deviation of the reinforcement cage from the design position; c) availability of a sludge layer in a pile head; d) violation of pile integrity; e) absence of a protective layer of reinforcement; f) formation of voids and caverns under the influence of underground waters with local of constant head (so-called “weeping pile”).

Let us list some technological defects that have a significant effect on the load-bearing capacity of piles: cold joints, caverns, voids during concreting; necking or bulging in the pile body; shrinkage or force-induced cracks; effect of “weeping piles”; non-uniform pile shaft formation in terms of density and material due to violations of concreting technology, etc.

In case of bored piles, the defects mentioned cannot be detected visually since they are hidden and localized along the length of the pile shaft. To solve the task, non-destructive testing and drilling-out of cores from the pile shaft are performed.

Drilling-out of cores remains a direct method of integrity testing for cast-in-situ piles (Figure 10). Since it is a traditional method, let us turn our attention to its modern peculiarities. To collect core samples, core barrels with diamond or carbide drill bits are used. The cores are then marked and a sampling report is made that includes the pile number and the number of samples with their diameter and depth indicated. The cores are tested for compression in the same way as concrete samples.



a) b)

Figure 10. A pile hole used for core sampling (a) and a drilled-out core (b).

DOI: 10.23968/2500-0055-2020-5-2-38-45

One of the modern methods of pile integrity analysis, which makes it possible to determine the defect nature and its location along the pile length, is the seismoacoustic method. The principle of seismoacoustic instruments' operation is based on recording the parameters of elastic waves generated in piles by means of impact pulse. A wave is generated that propagates through the pile body at a certain velocity *V*, partly reflecting from the interface between the two media (e.g. concrete and soil) and the defects. The reflection of the wave is caused by a change in the acoustic impedance determined by the following equation:

$$Z=A\sqrt{(\rho \cdot E)} \quad ,$$

where *A* is the area of pile cross-section; ρ is material density; *E* is the modulus of elasticity.

The reflected wave returns to the top of the pile and is recorded by an accelerometer (acceleration sensor), which, in turn, converts the waves generated by the wave exciter into a reflectogram (sound wave velocity vs. pile length or time graph) (Figure 11).

a)

b)

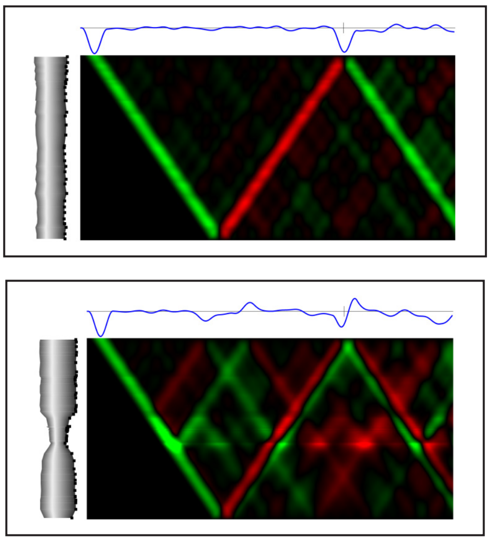


Figure 11. Reflectograms for a pile without defects (a) and for a pile with a necking defect (b).

In geotechnical practice, the ultrasonic flaw detection method is used for the integrity testing of drilled piles. It is based on the principles of ultrasonic wave velocity variation, the shape and amplitude of received signals depending on the physical and mechanical characteristics as well as the structure of the medium.

When applying this method, special tubes welded to the reinforcement cage are installed in a pile, which then used to conduct investigations. Concrete integrity in a pile can be assessed based on the energy transmission time and the energy value. If these parameters are constant or slightly vary with the penetration depth, it can be concluded that the structure is homogeneous. An increase in the signal transmission time and a decrease in the wave energy indicate the presence of defects, which is also shown on the instrument display.

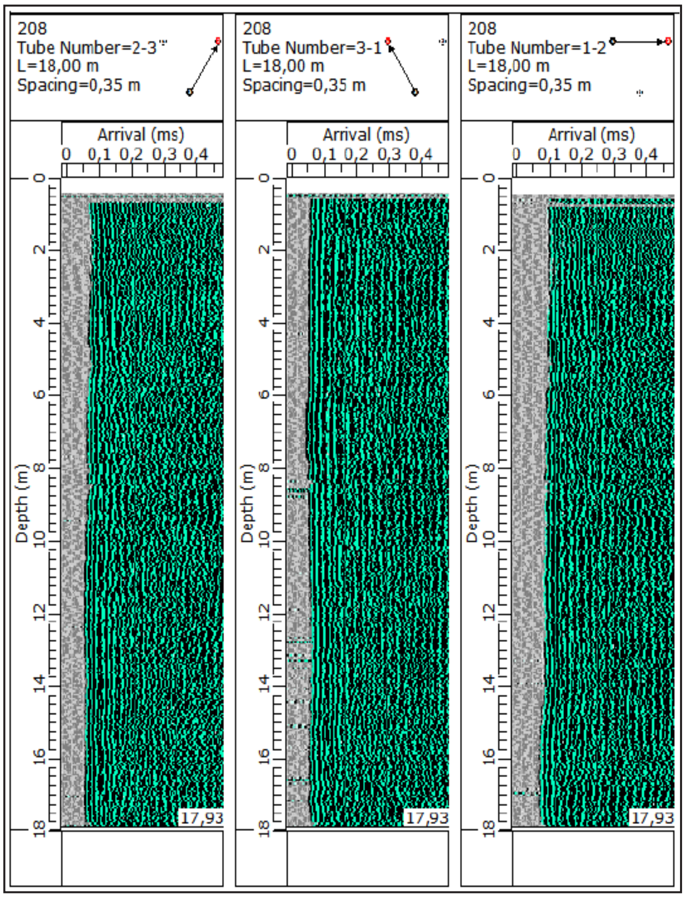


Figure 12. Ultrasonic scanning of a pile.

Conclusions

As experience in the integrity testing of cast-in-situ piles shows, the use of the ultrasonic and seismoacoustic non-destructive methods to determine pile integrity and pile installation depth is regulated by the corresponding documents and required in modern construction to detect defects and destruction of pile foundations to be installed. It should be noted that no regulations have been developed yet that would define the specific features of pile integrity testing for various technologies of pile construction in soft water-saturated soils, which makes the research conducted by the authors relevant and in demand in practice.

Due to the increasing application of bored piles, a need arises to control the depth of pile penetration into the bearing soil layer (reaching the design penetration depth).

In our opinion, the ultrasonic and seismoacoustic methods of testing are the most cost-efficient, less labor-consuming, and effective on construction sites. Interestingly, the methods used today for pile foundations' testing have their own characteristic features, require studying their applicability, establishing a relationship with the conditions of pile construction, and performing a correct interpretation of the results obtained in different soil conditions.

References

Arkhipov, A. G. and Matinyan, A. A. (2017). Complex of ultrasonic and seismoacoustic methods in the diagnosis of the condition of piles and slurry walls. In: *Inspection of buildings and structures: problems and solutions. VIII International Scientific and Practical Conference.* Saint Petersburg: Peter the Great St. Petersburg Polytechnic University, pp. 5–12.

Chernyakov, A. V., Bogomolova, O. V., Kapustin, V. V., Istratov, V. A. and Bobachev, A. A. (2013). Using a complex of geophysical and geotechnical methods for organization of quality control of “hidden” works and monitoring during large-scale urban construction. *Geotechnics*, 1, pp. 4–21.

Dashko, R. E., Aleksandrova, O. Yu., Kotyukov, P. V. and Shidlovskaya, A. V. (2011). Peculiarities of engineering and geological conditions in Saint Petersburg. *Razvitiye Gorodov i Geotekhnicheskoye Stroitelstvo*, 1.

Fursa, V. M. (1975). *Structural properties of soils in Leningrad*. Leningrad: Stroyizdat, 142 p.

Gaydo, A. N. and Ilyin, Ya. V. (2014). Specifics of using seismic acoustic control of pile foundations. In: *Modern geotechnologies in construction and their R&D support. Proceedings of the International Scientific and Practical Conference dedicated to the 80th anniversary of the Department of Geotechnics (Department of Foundation and Soil Engineering of the Leningrad Civil Engineering Institute) and the 290th anniversary of the Russian science*. Part 2. Saint Petersburg: Saint Petersburg State University of Architecture and Civil Engineering, pp. 51–58.

Mangushev, R. A. and Osokin, A. I. (2010). *Geotechnics of Saint Petersburg*. Moscow: ASV Publishing House, 259 p.

Mangushev, R. A. and Ponomaryov, A. B. (2014). For quality control issues manufacturing and acceptance of bored cast-in-place pile piles. *PNRPU Construction and Architecture Bulletin*, 3, pp. 88–111.

Mangushev, R. A., Ershov, A. V. and Osokin, A. I. (2007). *Modern pile technologies*. Moscow: ASV Publishing House; Saint Petersburg: Saint Petersburg State University of Architecture and Civil Engineering, 160 p.

Mangushev, R. A., Konyushkov, V. V. and D’yakonov, I. P. (2014). Analysis of practical application of screw-in cast piles. *Soil Mechanics and Foundation Engineering*, 51 (5), pp. 227–233. DOI: 10.1007/s11204-014-9281-9.

Mangushev, R. A., Osokin, A. I. and Sontnikov, S. N. (2018*). Geotechnics of Saint Petersburg. Experience of construction in soft soils*. Moscow: ASV Publishing House, 386 p.

Ministry of Construction, Housing and Utilities of the Russian Federation (2017). Regulations SP 45.13330.2017. Earthworks, grounds and footings. Revised edition of Construction Rules and Regulations SNiP 3.02.01-87. Moscow: Minstroy of Russia, 171 p.

Ministry of Construction, Housing and Utilities of the Russian Federation (2019). Regulations SP 63.13330.2018. Concrete and reinforced concrete structures. General provisions. Construction Rules and Regulations SNiP 52-01-2003 (with amendments). Moscow: Standartinform, 143 p.

Ministry of Regional Development of the Russian Federation (2011). Regulations SP 24.13330.2011. Pile foundations. Revised edition of Construction Rules and Regulations SNiP 2.02.03-85 (with amendments). Moscow: Minregion of Russia, 85 p.

Mukhin, A. A., Churkin, A. A. and Lozovskiy, I. N. (2018). Limitations of application area of low strain pile integrity testing. *Transport Construction*, 9, pp. 20–24.

Potapov, A. I., Syasko, V. A. and Pugachev, A. A. (2018). *Non-destructive testing tools and methods: a study guide*. Saint Petersburg: Polytekhnica-Print Printing House, 400 p.

Tatarinov, S. V., Voznesenskaya, E. S., Serebryakova, A. B., Lykov, A. V. and Len’shina, O. E. (2008). The use of seismo-acoustic method for control of piles quality. *Industrial and Civil Engineering*, 6, pp. 44–48.

DOI: 10.23968/2500-0055-2020-5-2-38-45

ОСОБЕННОСТИ УСТРОЙСТВА И КОНТРОЛЯ КАЧЕСТВА СВАЙНЫХ ОСНОВАНИЙ В ИНЖЕНЕРНО-ГЕОЛОГИЧЕСКИХ УСЛОВИЯХ САНКТ-ПЕТЕРБУРГА

Елизавета Сергеевна Лосева[1]*, Анатолий Иванович Осокин[2], Даниил Анатольевич Миронов[2], Иван Павлович Дьяконов[2]

[1]Санкт-Петербургский горный университет
Васильевский остров, 21 линия, 2, Санкт-Петербург, Россия.

[2]Санкт-Петербургский государственный архитектурно-строительный университет,
2-я Красноармейская ул., 4, Санкт-Петербург, Россия.

*E-mail: elizaveta_loseva@mail.ru

Аннотация

В данной статье обзорно рассматриваются различные методы устройства свайных фундаментов на территории Санкт-Петербурга в условиях сложного геологического строение, приведены различные методы контроля качества выполняемых свайных оснований. Обозначены условия, в которых формировалось геологическое строение территории города Санкт-Петербурга. Приведены основные факторы, влияющие на выбор видов фундаментов и методы его устройства, описаны свойства грунтов, которые оказывают влияние на качество выполняемых свай. **Методы.** Рассмотрены различные методы устройства свай по технологиям бурения: сваи, выполняемые в грунте, сваи заводского изготовления, сваи с уплотнением грунта и его извлечением. Описаны также различные методы контроля качества выполненных свай: сейсмоакустический, ультразвуковой. **Выводы.** По результатам работы сделан вывод о критической необходимости повсеместного использования методов для контроля качества свай и расширения спектра применяемости данных методов. **Обсуждение.** К обсуждению предлагается усовершенствование методов контроля сплошности свайных оснований, увеличение их практического применения на строительных площадках, изучение возможности их применения для контроля не только наличия дефектов в самой свае, но корректности их исполнения и качества применяемых материалов.

Ключевые слова

Геология, фундаменты, свайные технологии, методы контроля.