Geotechnical Engineering and Engineering Geology

SIDE FRICTION OF SANDY AND CLAY SOILS AND THEIR RESISTANCE UNDER THE TOE OF DEEP BORED PILES

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Abstract

Introduction: Saint Petersburg is characterized by complex engineering and geological conditions due to the presence of a significant mass (with a thickness of 20…30 m or more) of highly deformable soils with deformation moduli of 5…10 MPa. Besides, due to long-term geological processes that took place in the territory of Saint Petersburg thousands of years ago, these soils are extremely unevenly distributed in depth and area of occurrence. However, according to modern requirements for city development, deeper underground structures and higher buildings are needed. In terms of geotechnical solutions, it is possible to meet these requirements by using deep piles. **Purpose of the study:** The authors of the paper made an approximate brief classification of the geological conditions of Saint Petersburg based on the genesis, depth of occurrence, and physical and mechanical properties, and developed a method for more accurate calculations of the bearing capacity of deep bored piles. **Methods:** In the course of the study, the authors performed statistical processing of 600 values of the bearing capacity of bored piles, calculated according to the requirements of standards and determined by the results of field tests. In addition, they performed a non-linear extrapolation of side friction and resistance values (for soils with a depth of up to 100 m). **Results:** The paper presents the assessment of the bearing capacity of bored piles depending on their depth in glacial moraine and pre-quaternary vendian deposits. Using the nonlinear extrapolation, the authors calculated the side friction and resistance under the toe of bored piles for further design of pile foundations with deep bored piles (at a depth of up to 100 m). **Discussion:** According to statistical studies, the actual bearing capacity of bored piles is significantly higher than the design one calculated according to the requirements of corresponding standards (by 1.6...2.6 times). This is due to the fact that soils with significantly differing strength and deformation characteristics are located along the side and under the toe of bored piles. The stronger the soil where the most part of the pile is located, the more the bearing capacity error is (towards underestimation). The paper presents studies confirming this statement.

Keywords

Glacial moraine and pre-quaternary vendian deposits, side friction, resistance under the pile toe, bearing capacity of bored piles at a depth of up to 100 m.

Introduction

The authors of the paper conducted a large-scale analysis of archival materials related to engineering and geological surveys performed by GUP “Trest GRII” (State Unitary Enterprise “Geodetic and Engineering Survey Trust”) and ZAO “LenTISIZ” (Closed Joint-Stock Company “Leningrad Engineering and Construction Survey Trust”) in Saint Petersburg over the past 50 years. Following the analysis results, an approximate classification of soils was made based on their genesis, depth of occurrence, and physical and mechanical properties. In general, in terms of genesis, soils in Saint Petersburg can be divided into four main sedimentary complexes (Dashko et al., 2011; Filippov and Spiridonov, 2009; Shashkin, 2014):

0. Technogenic deposits (tg_{IV}) — located in the upper part of the soil mass, starting from the level of the grade elevation of the ground. They are characterized

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by extremely uneven stratification in depth and area of occurrence. Due to heterogeneous configuration, their strength and deformation properties differ significantly. As a rule, during surveys, these soils are not assigned any characteristics, which is why they are usually not used as load-bearing soils and bases under the foundations of buildings and structures. Their thickness usually does not exceed 1.5…5 m (but it may be higher in some areas).

1. River and marine deposits (*al_{IV}, ml_{IV}*) — located under technogenic deposits. As a rule, they are represented by water-saturated silty sands and sandy loams, sometimes clay loam. Silty sands are usually characterized by medium strength and deformability (in contrast to lower values of sandy loams and clay loams' characteristics). These soils are located under the foundation bottom of most historical buildings in Saint Petersburg (with a construction and operation period of more than 100 years). Their thickness is usually insignificant and amounts to 1…5 m (however, it can be higher). It should be noted that, according to modern design requirements, these soils cannot be used as the bearing layer or the base for foundations of permanent facilities in every instance. This is due to their insignificant thickness and presence of highly deformable lake-glacial deposits underlying the base of river and marine deposits.

2. Lake-glacial deposits (*lg_{IV}*) — can be located directly under technogenic deposits or under river or marine deposits (although they may interstratify with those). They are mainly represented by sandy loams and clay loams. Their strength and deformation characteristics are extremely unfavorable: these soils are highly deformable, poorly permeable, overmoistened, thixotropic and creeping. Long-term geological processes of their formation and historical processes of Saint Petersburg development and construction are responsible for the fact that lake-glacial deposits represent the underlying layers of bearing soils under most of the foundations of buildings and structures constructed on a natural base (from the foundation of Saint Petersburg in 1703 to the present time). It is a consequence of the long-term development of differential settlements in the foundations of historical and modern buildings constructed on a natural base or on short piles (placed in such soils).

3. Glacial moraine deposits (*g_{III}*) — represented mainly by sandy loams and clay loams; located, as a rule, under lake-glacial deposits. These soils are characterized by medium strength (as compared with overlying soils). However, characteristics of glacial deposits vary significantly due to different genesis, structure, composition, depth, thickness, and extension. Glacial deposits can be classified as mainly medium-deformable but, in some cases, they can also be highly deformable for the reasons outlined above. The majority of buildings and structures on pile foundations (both constructed and under construction) in Saint Petersburg have glacial moraine deposits as bearing layers under the pile toe.

4. Pre-quaternary vendian clays (*vkt_2*) — the most durable and reliable layer, which is represented by solid and semi-solid clays. The top of this layer is extremely uneven in depth (usually at significant depths from 20 m and deeper). However, when penetrated, the top of this layer is usually homogeneous in terms of its properties: engineering and geological elements below have strength and deformability not less than those of overlying elements, and sometimes these values even increase in depth. We can state that the foundations based on undisturbed pre-quaternary Vendian clays will have a significant bearing capacity and low deformations. As already mentioned above, the main disadvantage of this complex is the uneven depth of the top and the significant depth of occurrence in some areas of Saint Petersburg (up to 60...80 m or more).

Figures 1 and 2 below show schematic maps of Saint Petersburg indicating the depth of the top of glacial moraine and pre-quaternary Vendian deposits. Table 1 shows the approximate values of the physical and mechanical characteristics of the main geological deposits in Saint Petersburg depending on their genesis (highly deformable, medium- deformable and poorly deformable soils are highlighted in different colors).

Subject, tasks, and methods

The subject of the study is the bearing capacity of deep bored piles subjected to a vertical compressive load. To perform the study, the authors developed a brief classification of genetic complexes of Saint Petersburg soils (Figures 1, 2, Table 1). Then, they set and solved the following **tasks:**

- classified results of 600 field tests of bored piles, performed by OOO "PKTI Fundament-Test" for the period from 2000 to 2020, and performed their statistical processing;
- constructed comparative diagrams for the bearing capacity of bored piles, calculated according to the requirements of standards and obtained as a result of field tests;
- determined the side friction of sandy and clay soils depending on the soil properties and pile depth of up to 100 m;
- determined the resistance of sandy and clay soils under the pile toe depending on the soil properties and pile depth of up to 100 m.

As the main research **methods**, the authors used statistical processing of 600 values of the pile bearing capacity, calculated according to the requirements of standards and obtained as a result of field tests (using the least square method). Besides, they performed a non-linear extrapolation of friction and resistance values to a depth of 100 m, depending on the physical properties of soils (based on the corresponding tables in Regulations SP 24.13330 "Pile foundations", limiting the pile length to 40 m).

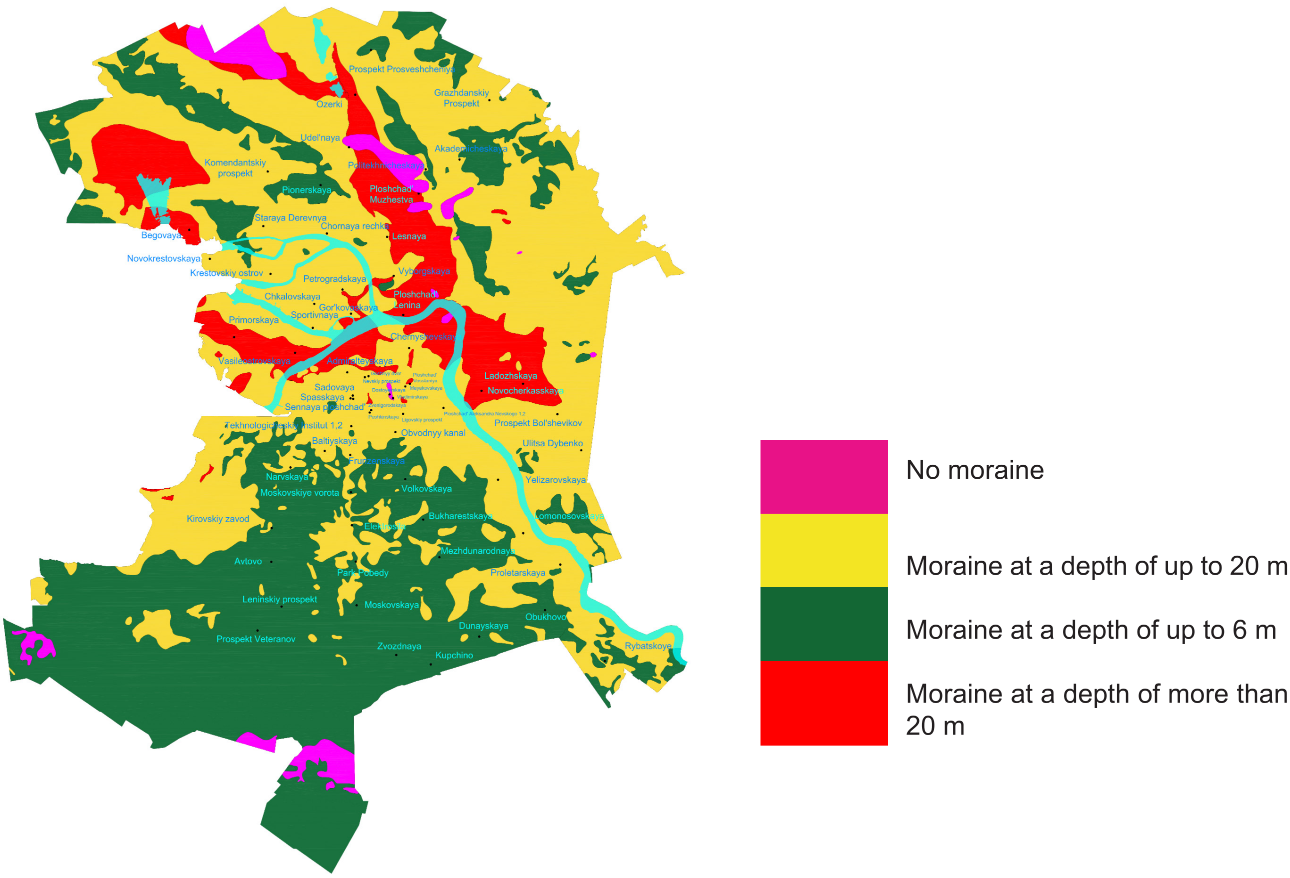

Figure 1. Schematic map of Saint Petersburg with color representation of the depth of the top of glacial Moraine deposits

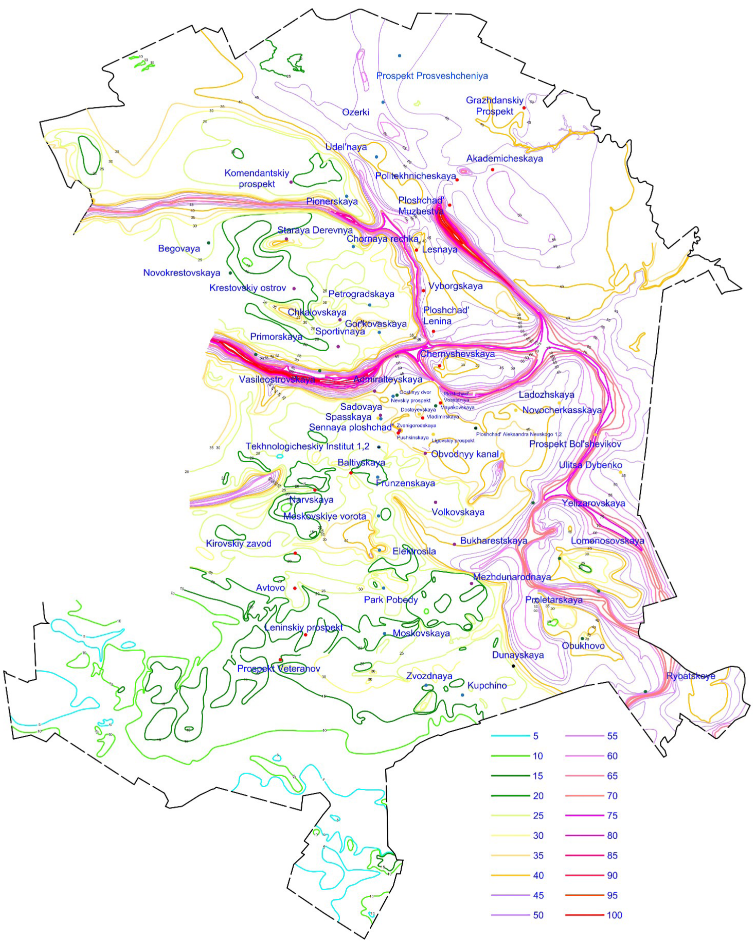

Figure 2. Schematic map of Saint Petersburg with isolines for the depth of the top of pre-quaternary vendian deposits, m

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Table 1. Approximate values of physical and mechanical characteristics of soils in Saint Petersburg depending on their genesis (red color indicates highly deformable soils, yellow color indicates medium-deformable soils, and green color indicates poorly deformable soils)

Parameter	Designation, unit	Name of soil genesis			
		1. Properties of river and marine deposits (*al_{IV}, ml_{IV}*)	**2. Properties of lake-glacial deposits (*lg_{IV}*)**	**3. Properties of glacial moraine sandy loams and clay loams (*g_{III}*)**	**4. Properties of pre-quaternary vendian clays (*vkt_2*)**
Specific weight	γ, kN/m³	17…20	17…20	18…20	20…22
Moisture	*W, %*	50…30	50…30	30…20	20…10
Void ratio	*e*, unit fraction	more than 1.0…0.6	more than 1.0…0.6	0.8…0.5	0.5…0.3
Liquidity index	I_L, -	more than 1.0…0.75 (for clay soils)	more than 1.0…0.75 (for clay soils)	0.75…0.25	less than 0.25
Specific cohesion	*c, kPa*	1…20 (for sand)	5…20	20…50	50…100 and higher
Internal friction angle	φ, °	20…30 (for sand)	5…20	15…30	15…30
Deformation modulus	*E*, MPa	5…15	5…15	15…40	20…100 and higher

Results and discussion

The bearing capacity of a bored pile mainly depends on two components: side friction forces and soil resistance under the pile toe (Gotman et al., 2017; Ilyichev and Mangushev, 2016; Konyushkov et al., 2019; Mangushev et al., 2010, 2014; Osokin et al., 2019; Shulyatyev, 2016; Shulyatyev et al., 2017; Ter-Martirosyan, 2009; Ter-Martirosian et al., 2017; Ter-Martirosyan et al., 2015):

$$F_d = f\left(\sum f_i; R_i\right) \tag{1}$$

With an increase in the pile depth (Figure 3), the side friction and the resistance under the pile toe can be classified into three characteristic cases as shown in expressions (2) and (3):

$$\sum f_1 < \sum f_2 < \sum f_3 \tag{2}$$

$$R_1 < R_2 < R_3 \tag{3}$$

Figure 3 shows a provisional classification for the bearing capacity of bored piles (three main schemes) depending on the pile depth in weak soils, moraine and Vendian deposits.

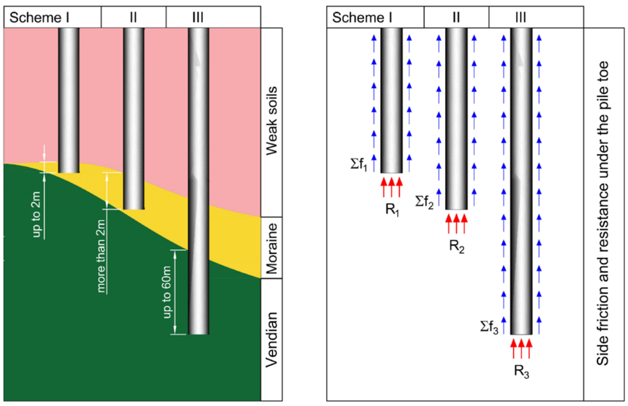

Figure 3. Provisional classification for the bearing capacity of bored piles (three main schemes) depending on the pile depth in weak soils, moraine and vendian deposits

We analyzed the extensive results of the field tests of bored piles, performed in Saint Petersburg by OOO “PKTI Fundament-Test” during 2000–2020. In total, approximately 600 tests were processed. After that, we calculated the bearing capacity of bored piles using the method suggested by Regulations SP 24.13330 “Pile foundations”. Then, we constructed comparative diagrams for the bearing capacity of piles based on the field tests and the bearing capacity of piles calculated according to the requirements of standards. Figures 4, 5, 6 show results of statistical processing of bearing capacity ratios obtained by the least square method. All comparative diagrams clearly show that, depending on the location of a pile in the ground (schemes I, II, III in Figure 3), the actual bearing capacity of a pile determined based on the results of the field tests, increases by 1.6…2.6 times. This fact indicates that the greater the pile depth is (especially if it is a solid ground, e.g. pre-quaternary Vendian clay according to scheme III), the more the actual bearing capacity of the pile differs from that calculated according to the requirements of standards. We expanded the well-known table of soil frictions and resistances depending on the physical properties of soils from Regulations SP 24.13330 “Pile foundations”. This table is characterized by a pile depth limit to 40 m. Using a nonlinear extrapolation, we constructed graphs for the distribution of side friction and soil resistance under the pile toe up to a depth of 100 m. Tables 2, 3 and Figures 7, 8 show results of such nonlinear extrapolation of friction and resistance values. Taking into account the fact that pile foundations for high-rise buildings currently require a depth of more than 40 m (e.g. piles for the Lakhta Center have a depth of 85 m from the grade elevation of the ground), these tables and graphs can be very useful for designers and builders.

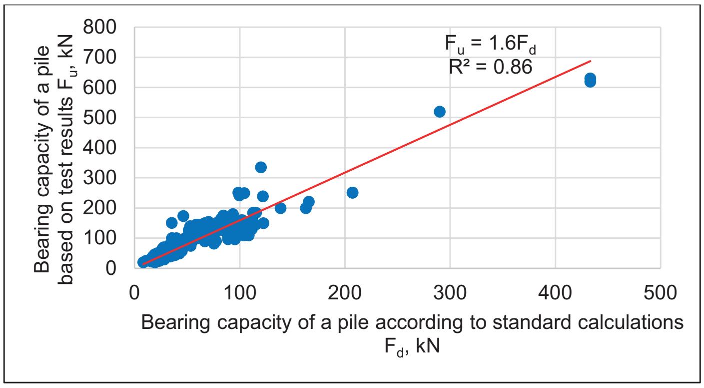

Figure 4. Comparative diagram for the bearing capacity of bored piles based on the results of field tests and bearing capacity of bored piles calculated according to standards (scheme I)

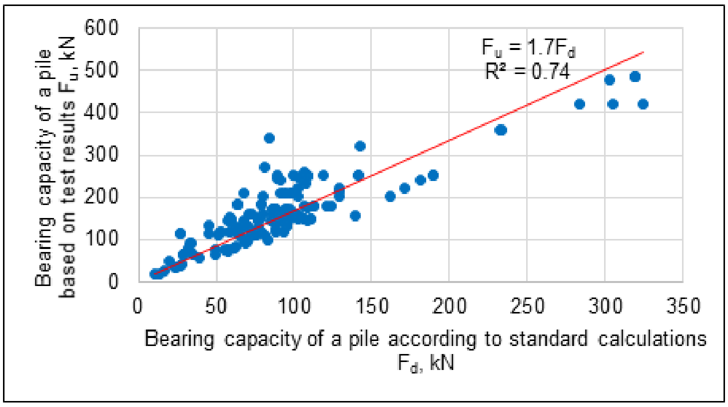

Figure 5. Comparative diagram for the bearing capacity of bored piles based on the results of field tests and bearing capacity of bored piles calculated according to standards (scheme II)

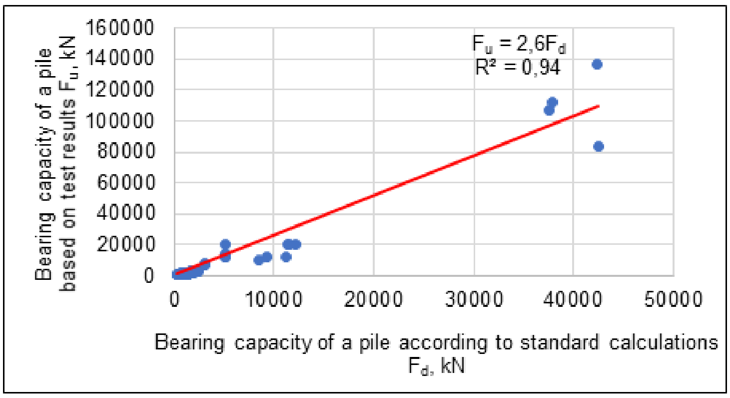

Figure 6. Comparative diagram for the bearing capacity of bored piles based on the results of field tests and bearing capacity of bored piles calculated according to standards (scheme III)

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Table 2. Side friction of sandy and clay soils

Design side friction f, kPa					
Medium density sands	coarse and medium	Clay soils with liquidity index I_L	0.2	$f = 34.716z^{0.2861}$	$R^2 = 0.9936$
	fine		0.3	$f = 24.349z^{0.2902}$	$R^2 = 0.9898$
	silty		0.4	$f = 16.917z^{0.3058}$	$R^2 = 0.9820$
	-		0.5	$f = 14.259z^{0.2644}$	$R^2 = 0.9477$
	-		0.6	$f = 10.503z^{0.2261}$	$R^2 = 0.8386$
	-		0.7	$f = 5.6088z^{0.2518}$	$R^2 = 0.8369$
	-		0.8	$f = 5.1753z^{0.1694}$	$R^2 = 0.6849$
	-		0.9	$f = 4.148z^{0.2027}$	$R^2 = 0.6752$
	-		1.0	$f = 3.241z^{0.2372}$	$R^2 = 0.6844$

Notes:
1. *z* is the average depth of the soil layer, m.
2. *f* is the design side friction, kPa.
3. When calculating the design side friction f_i, the soil layers shall be divided into homogeneous layers with a thickness not exceeding 2 m.
4. The design side friction values f for dense sands shall be increased by 30% compared with the values given in the table.
5. The design friction values for sandy loams and clay loams with a void ratio e < 0.5 and clays with a void ratio e < 0.6 shall be increased by 15% compared with the values given in the table at any values of the liquidity index.

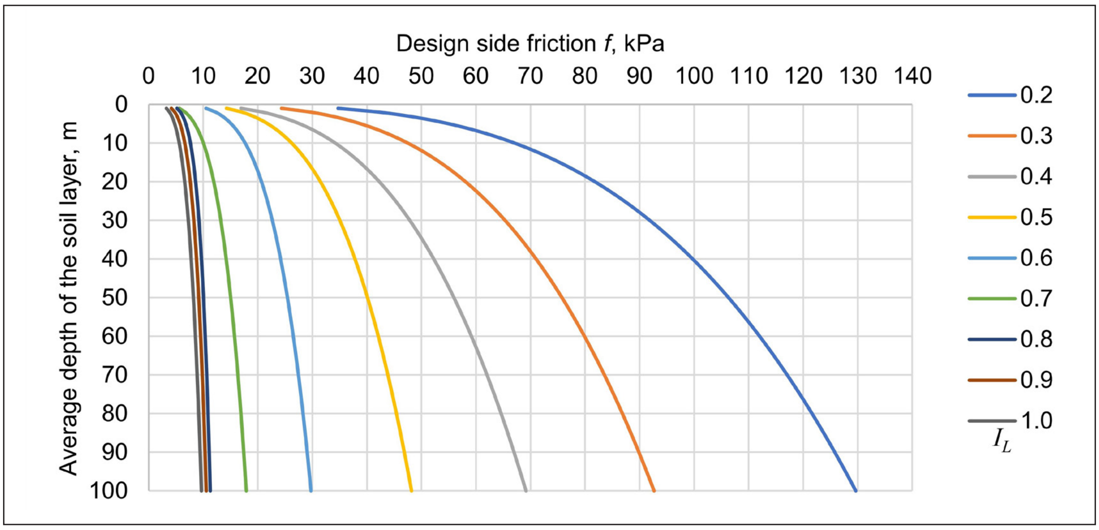

Figure 7. Graph for the distribution of side friction forces up to a depth of 100 m

Table 3. Resistance of sandy and clay soils under the toe of bored piles

Design resistance under the toe of bored piles R, kPa					
Medium density sands	Gravelly	Clay soils with liquidity index I_L	0.0	$R = 0,7287z^2 + 67,372z + 636,88$	$R^2 = 0,9998$
	Coarse		0.1	$R = 0,4504z2 + 69,632z + 500,81$	$R^2 = 0,9996$
	-		0.2	$R = 0,2499z^2 + 67,026z + 408,23$	$R^2 = 0,9984$
	Medium		0.3	$R = 0,0403z^2 + 65,742z + 302,9$	$R^2 = 0,9998$
	Fine		0.4	$R = -0,2019z^2 + 66,531z + 171,75$	$R^2 = 0,9991$
	Silty		0.5	$R = -0,0861z^2 + 59,195z + 110,29$	$R^2 = 0,9985$
	-		0.6	$R = -0,2276z^2 + 51,595z + 99,61$	$R^2 = 0,9985$

Notes:
1. *z* is the depth of the pile toe, m
2. *R* is the design resistance under the toe of a bored pile, kPa
3. for intermediate values of the liquidity index I_L for clay soils, the *R* values in the table are determined by interpolation.

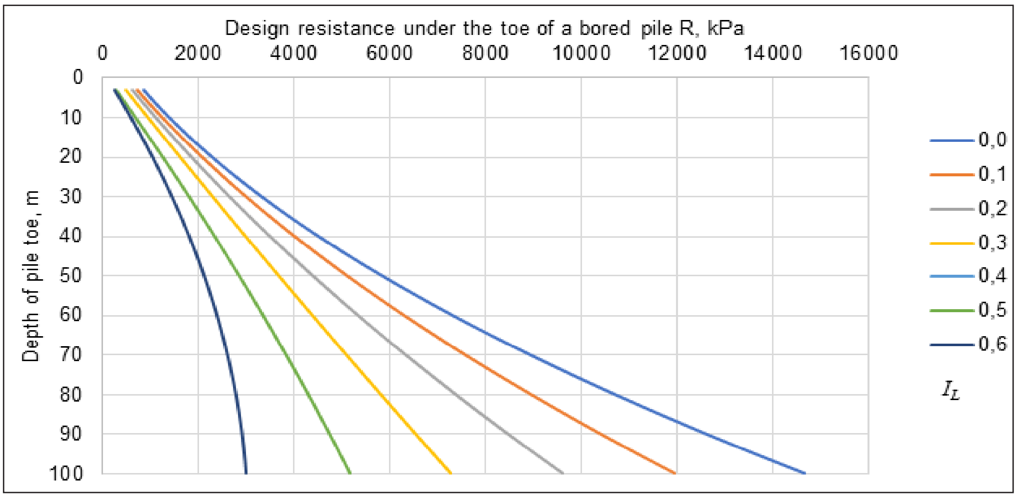

Figure 8. Graph for the distribution of soil resistance under the toe of a bored pile up to a depth of 100 m

Conclusions

Based on the archival materials of geological surveys performed by GUP "Trest GRII" (State Unitary Enterprise "Geodetic and Engineering Survey Trust") and ZAO "LenTISIZ" (Closed Joint-Stock Company "Leningrad Engineering and Construction Survey Trust"), the authors developed the schematic maps for the depth of the top of glacial moraine deposits and pre-quaternary Vendian clays, which are typically load-bearing soils of pile foundations. At the stage of preliminary design of foundations, it is possible to use these maps and determine the length of piles based on the location of a construction site in Saint Petersburg.

Based on the statistical processing of the results of 600 field tests of bored piles, performed by OOO "PKTI Fundament-Test", it was found that the actual bearing capacity of bored piles significantly exceeds the design one, calculated according to the requirements of corresponding standards (by 1.6...2.6 times). With an increase in the depth of piles in stronger soils, the actual bearing capacity and the design one can differ by 2.6 times.

For more accurate calculations of the bearing capacity of deep bored piles, the authors performed the nonlinear extrapolation of side friction and resistance (under the toe of piles up to a depth of 100 m) values depending on the physical characteristics of soils where the piles are located. The results of the nonlinear extrapolation are summarized in tables and graphs, the use of which will make it possible to perform more accurate calculations of the bearing capacity of deep bored piles.

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References

Dashko, R. E., Aleksandrova, O. Yu., Kotyukov, P. V. and Shidlovskaya, A. V. (2011). Specifics of engineering and geological conditions in Saint Petersburg. *Urban Development and Geotechnical Construction,* 1, pp. 1–47.

Filippov, N. B. and Spiridonov, M. A. (eds.) (2009). *Geological Atlas of Saint Petersburg.* Saint Petersburg: Komilfo, 57 p.

Gotman, N. Z., Alekhin, V. S. and Sergeev, F. V. (2017). Determination of bearing capacity of piles in the group. *PNRPU Bulletin. Construction and Architecture*, 8 (3), pp. 13–21. DOI: 10.15593/2224-9826/2017.3.02.

Ilyichev, V. A. and Mangushev, R. A. (eds.) (2016). *Geotechnical engineer's reference book. Bases, foundations, and underground constructions*. 2nd edition. Moscow: ASV Publishing House, 1040 p.

Konyushkov, V. V., Kondratieva, L. N., Kirillov, V. M. and Le Van Trong (2019). Accelerated methods for determining the bearing capacity of drill piles. *Bulletin of Civil Engineers,* 3, pp. 63–71. DOI: 10.23968/1999-5571-2019-16-3-63-71.

Mangushev, R. A., Ershov, A. V. and Osokin, A. I. (2010). *Modern pile technologies. 2nd edition.* Moscow: ASV Publishing House, 240 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.

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

Osokin, A. I., Konyushkov, V. V., Dyakonov, I. P. and Le, V. T. (2019). Evaluation of the bearing capacity of the drilling pile for construction of a skyscraper with a developed underground structure. *Bulletin of Civil Engineers,* 4, pp. 58–67. DOI: 10.23968/1999-5571-2019-16-4-58-67.

Shashkin, A. G. (2014). *Design of buildings and underground structures in complex geological conditions of Saint Petersburg.* Moscow: Publishing house "Academicheskaya Nauka" — Geomarekting, 352 p.

Shulyatyev, O. A. (2016). *Bases and foundations of high-rise buildings.* Moscow: ASV Publishing House, 392 p.

Shulyatyev, O. A., Mozgacheva, O. A., Pospekhov, V. S. (2017). *Development of urban underground spaces.* Moscow: ASV Publishing House, 510 p.

Ter-Martirosian, A. Z., Ter-Martirosian, Z. G. and Luzin, I. N. (2017). Stress-strain condition of base of deep foundations. *PNRPU Bulletin. Construction and Architecture,* 8 (2), pp. 96–103. DOI: 10.15593/2224-9826/2017.2.09.

Ter-Martirosyan, Z. G. (2009). *Soil mechanics.* Moscow: ASV Publishing House, 553 p.

Ter-Martirosyan, A. Z., Ter-Martirosyan, Z. G. Trinh, T. V. and Luzin, I. N. (2015). Sediment and bearing capacity of long pile. *Vestnik MGSU (Monthly Journal on Construction and Architecture),* 10 (5), pp. 52–61.

СОПРОТИВЛЕНИЕ ПЕСЧАНЫХ И ГЛИНИСТЫХ ГРУНТОВ ПО БОКОВОЙ ПОВЕРХНОСТИ И ПОД ОСТРИЕМ БУРОВЫХ СВАЙ ГЛУБОКОГО ЗАЛОЖЕНИЯ

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Аннотация

Санкт-Петербург характеризуется сложными инженерно-геологическими условиями из-за наличия значительной толщи (20…30 м и более) сильнодеформируемых грунтов с модулями общей деформации 5…10 МПа. Кроме этого, вследствие длительных геологических процессов, происходивших на территории Санкт-Петербурга тысячи лет назад эти грунты крайне неравномерно распределены по глубине и площади залегания. Однако современные требования по развитию города требуют более глубоких подземных сооружений и более высоких зданий. Выполнить эти требования с точки зрения геотехнических решений возможно путем применения свай глубокого заложения. **Цель исследования.** Краткая приблизительная классификация геологических условий Санкт-Петербурга по генезису, глубине залегания и ориентировочным физико-механическим свойствам и разработка методики для более точных расчетов несущей способности буровых свай глубокого заложения. **Методы.** В исследовании была применена статистическая обработка 600 значений несущей способности свай, вычисленной по требованиям норм и определенной по результатам полевых испытаний. Кроме этого, была выполнена нелинейная экстраполяция трений и сопротивлений грунтов до глубины 100 м. **Результаты.** В статье представлены результаты исследования: оценка несущей способности буровых свай в зависимости от глубины их расположения в ледниковых моренных и дочетвертичных вендских отложениях. Далее путем нелинейной экстраполяции определены расчетные трения по боковой поверхности и сопротивления под острием буровых свай для проектирования свайных фундаментов из буровых свай глубокого заложения. **Обсуждение.** Фактическая несущая способность буровых свай значительно превышает расчетную, вычисленную по нормам (в 1,6…2,6 раза). На этапе предварительного проектирования фундаментов можно использовать карты глубин залегания кровли ледниковых моренных отложений и дочетвертичных вендских глин и проектировать длину свай исходя из месторасположения объекта строительства в Санкт-Петербурге. Результаты нелинейной экстраполяции сопротивления грунтов сведены в таблицы и графики, применение которых позволит более точно рассчитывать несущую способность буровых свай глубокого заложения.

Ключевые слова

Ледниковые моренные и дочетвертичные вендские отложения, трение грунтов по боковой поверхности свай, сопротивление грунтов под острием свай, несущая способность буровых свай по грунту с длиной до 100м.