

DEVELOPMENT OF METHODS FOR DESIGNING PILE FOUNDATIONS FOR MULTI-STOREY CIVIL BUILDINGS CONSTRUCTED ON MACROPOROUS SUBSIDENCE SOILS

*Maxim B. Marinichev*¹, *Nadezhda S. Nikitina*², *Anatoly I. Polishchuk*¹

¹ I.T. Trubilin Kuban State Agrarian University, Krasnodar, RUSSIA

² Moscow State University of Civil Engineering, Moscow, RUSSIA

Abstract: The study considers the methods (separate stages) of designing pile foundations made of driven reinforced concrete piles on macroporous subsidence soils of the second type of subsidence using multi-storey buildings as an example. The paper provides a brief description of the buildings under consideration, analyzes the soil conditions of construction, including data on physical, deformation, strength, subsidence characteristics of soils and methods of their determination. Using the calculation, it establishes the type of soil conditions in terms of subsidence, describes the method of selecting the type of piles and their length in macroporous subsidence soils. The data of experimental studies of bearing capacity of driven piles in macroporous subsidence soils, justification of the method of numerical studies of pile performance and theoretical evaluation of their bearing capacity are given.

Keywords: Driven piles, foundations, design, ground conditions of construction, soil properties, bearing capacity of piles, subsidence type of ground conditions, results of experimental and numerical studies

РАЗВИТИЕ МЕТОДОВ ПРОЕКТИРОВАНИЯ СВАЙНЫХ ФУНДАМЕНТОВ НА МАКРОПОРИСТЫХ ПРОСАДОЧНЫХ ГРУНТАХ ДЛЯ МНОГОЭТАЖНЫХ ГРАЖДАНСКИХ ЗДАНИЙ

*М.Б. Мариничев*¹, *Н.С. Никитина*², *А.И. Полищук*¹

¹ Кубанский государственный аграрный университет имени И.Т. Трубилина, г. Краснодар, РОССИЯ

² Московский государственный строительный университет, г. Москва, РОССИЯ

Аннотация: На примере многоэтажных зданий рассматриваются методы (отдельные этапы) проектирования свайных фундаментов из забивных железобетонных свай на макропористых просадочных грунтах второго типа по просадочности. Дается краткая характеристика рассматриваемых зданий, анализируются грунтовые условия строительства, включая данные о физических, деформационных, прочностных, просадочных характеристиках грунтов и методы их определения. Расчетом устанавливается тип грунтовых условий по просадочности, излагается метод выбора типа свай и их длины в макропористых просадочных грунтах. Приводятся данные экспериментальных исследований несущей способности забивных свай в макропористых просадочных грунтах, обоснование метода численных исследований работы свай и теоретической оценки их несущей способности.

Ключевые слова: Сваи забивные, фундаменты, проектирование, грунтовые условия строительства, характеристики грунтов, несущая способность свай, тип грунтовых условий по просадочности, результаты экспериментальных и численных исследований

INTRODUCTION

The authors of this study conduct research on substantiation of soil conditions and development of pile foundation design solutions for

construction of civil multi-storey residential buildings constructed on macroporous subsidence soils [1, 2, 3]. Such soils are widespread in Russia and other countries. They are found in the southern, south-eastern and south-western

regions of our country (Krasnodar Krai, Republic of Adygea, Volgograd Oblast, Stavropol Krai, Chechen Republic, Republic of Crimea, Zabaikalye, etc.). Therefore, they are often called as regional soils. The conditions of construction on such soils are referred to regional (or special). The article considers the methods (main stages) of pile foundation design on construction sites composed of macroporous subsidence soils using the example of civil buildings in Grozny with load-bearing walls and frame buildings [4, 5].

SOIL CONDITIONS OF A TYPICAL CONSTRUCTION SITE

The construction site is located in the Chechen Republic. The relief of the site is relatively flat, with absolute elevations of 285.5-286.5 m and a slight slope to the southwest. To find out the lithologic structure of the site 47 boreholes were drilled to a depth of 4 to 25 m and 5 pits up to 3.5 m deep were excavated. The engineering-geological section of the experimental site is represented by the following soils (engineering-geological elements):

1. Soil-vegetation layer, thickness 0.2-0.4 m.
2. Below there is a layer of low-moisture, macroporous subsidence loam, from semi-hard to hard consistency, yellow-brown color with inclusions of gypsum and carbonate salts (EGE-1). The thickness of this layer varies from 9.6 to 11.8 m.
3. At a depth of about 10.7 m from the surface there is a 1.9-2.5 m thick layer of buried soil (EGE-2) represented by hard, semi-hard, subsidence loam, dark brown in color with abundant inclusion of salts.
4. Below, at a depth of about 11.5 - 14.3 m, there is a layer of low-moisture, macroporous loam of tight plastic, yellow-brown color, with inclusion of carbonate salts. The thickness of this layer varies from 6.9 - 7.7 m (EGE-3).
5. At a depth of 18.4 - 22.0 m from the surface there is a fine gravel with sandy fill (EGE-4). There is not groundwater up to a depth of 25 m.

PHYSICAL, DEFORMATION, STRENGTH AND SUBSIDENCE PROPERTIES OF SOILS

Since the foundations of civil buildings are supposed to be constructed on macroporous subsidence soils, the study of their properties at the design stage is envisaged on soils with different moisture content (natural and pre-moistened). To determine the physical, strength, deformation and subsidence properties of the base under consideration, soils were taken mainly in the form of monoliths and separate samples, specimens at the entire depth (72 monoliths) in accordance with the requirements of GOST 12071-2000 [6]. Soils (monoliths, samples) were taken from the base of natural composition (low-moisture) and after its preliminary soaking (wet). Hereinafter in the text the term “*low-moisture soils*” means macroporous base of natural composition at its natural moisture content ($S_r \leq 0.5$). “*Wet soils*” means macroporous base after its preliminary wetting ($0.5 \leq S_r \leq 0.8$).

For the proposed construction of civil multi-storey buildings, macroporous soils were soaked gradually for 25-30 days. For this purpose, a pilot site was prepared previously, where a pit with the plan size of 20 x 20 m and depth of 0.4 - 0.5 m was made (Grozny). The surface of the excavation before soaking was filled with fine crushed stone (fraction 3-10 mm) to a thickness of 7-10 cm. Along the perimeter of the pit, as well as along its area, wells with diameter up to 120 mm were made to a depth of 14-15 m, which were also backfilled with fine crushed stone. Wells on the area of the excavation were arranged on a grid of 4x4 meters. Water was supplied to the experimental site with a hose under low pressure. The flow rate was fixed by a water meter connected to the water supply system on the territory of the experimental site. The minimum volume of poured water was determined by calculation. Soaking was controlled visually and instrumentally by taking samples and soil samples from different depths and determining its weight moisture [7, 8, etc.].

The study of *physical properties* of soils was carried out according to the current regulatory documents and recommendations (GOST 5180-2015,

A.I. Polishchuk, M.B. Marinichev, 2023, etc.) [9, 10]. Analysis of the results of studies of properties of macroporous subsidence soils of the experimental site revealed that up to the depth of 15 m the change in their density and moisture content within each engineering-geological element (EGE-1, EGE-2) is insignificant, which does not exceed 3-5%. Consequently, the soil base can be considered practically homogeneous and the mean values of the considered physical characteristics for each engineering-geological element can be used for forecast calculations (Table 1).

Table 1 shows that the upper layer of low-moisture loam of natural composition (EGE-1)

belongs to the hard consistency state ($I_L \leq 0$), and the same layer of loam additionally moistened (wet) is characterized as soft-plastic ($I_L = 0.66$). After additional moistening (soaking) of the soil, complete filling of its pores with water did not occur. This is confirmed by the value of water saturation coefficient $S_r = 0.72$, which is less than $S_r < 0.8 \dots 1.0$. The characteristic of porosity coefficient e of low-moisture and wet soil indicates its macroporous (loose) state, which is confirmed by the values $e = 0.90 - 0.94$, which are close to the value $e = 1.0$.

Table 1. Physical properties of loess subsidence soils of the experimental site

Base soils, engineering geological elements (EGE)	Layer thickness, m	Density ρ , g/cm ³	Skeleton density ρ_d , g/cm ³	Natural moisture W , %	Density of particles ρ_s , g/cm ³	Porosity factor e ,	Water saturation factor S_r ,	Moisture at the liquidity limit W_L , %	Moisture at the plastic limit W_p , %	Plasticity index J_p , %	Liquidity index J_L ,
Hummocky loam, macroporous EGE-1	10,4	$\frac{1,59}{1,79}$	$\frac{1,41}{1,44}$	$\frac{12,5}{23,6}$	2,73	$\frac{0,94}{0,90}$	$\frac{0,36}{0,720}$	$\frac{0,94}{0,90}$	17,7	9,0	$\frac{< 0}{0,66}$
Dark brown loam (inter-layer), EGE-2	1,9-2,5	$\frac{1,70}{1,81}$	$\frac{1,49}{1,48}$	$\frac{14,2}{22,0}$	2,72	$\frac{0,82}{0,83}$	$\frac{0,47}{0,72}$	27,1	16,9	10,2	$\frac{< 0}{0,51}$
Yellow-brown loam, EGE-3	6,9-7,7	1,75	1,45	21,0	2,71	0,87	0,65	27,0	17,0	10,0	0,4
Shallow gravel, EGE-4	More than 5,0	-	-	-	2,68	0,65	-	-	-	-	-

Note. In the numerator - properties of low-moisture natural moisture soils, in the denominator - pre-moistened wet soils.

Deformation properties of macroporous subsidence soils (EGE-1, EGE-2, etc.) were determined in laboratory conditions using compression devices in accordance with the requirements of regulatory documents and standards: GOST 12248.4-2020, SP 22.13330.2016, GOST 23161-2012. [11-13]. Stages of loading on the soil samples were accepted in the range of 20 - 40 kPa until complete stabilization of settlements. Settlement in-

crement not exceeding 0.01 mm / day was adopted as a stabilization criterion. The maximum pressure on the soil samples in the experiments did not exceed 250 - 350 kPa.

Comparison of the values of total deformation modulus of subsidence soils within the depth up to 13-15 m shows that their values within each engineering-geological element differ insignificantly. The deviation at the same pressure interval varies

within 8-10%. In total, about 30 compression tests for low-moisture and wet macroporous subsidence soils were analyzed (Table 2). The analysis of the obtained results indicates that the values of the properties of the total deformation modulus of soils significantly depend on the moisture content, porosity, the magnitude of the applied pressure and structural strength of soils [14].

Table 2. Data on the results of compression tests of loess subsidence soils

Engineering-geological elements	Sample pressure interval, kPa	Values of total deformation modulus E of loess soils, MPa	
		low-moisture	wet
EGE-1	100...140	7,1	1,6
	140...200	11,4	1,0
	200...250	14,2	1,3
EGE -2	100...140	7,7	11,1
	140...200	12,4	10,9
	200...250	15,4	14,0
EGE -3	100...140	7,8	-
	140...200	12,5	-
	200...250	15,6	-
EGE -4	-	25	-

Strength properties of soils ϕ and c were determined by the single-plane shear test according to GOST 12248.1-2020. In the experiments the scheme of rapid shear under conditions of incomplete consolidation without preliminary

compaction of soil samples was used. Under this shear scheme the values of strength properties are the lowest compared to other test methods (M.Y. Abelev, 1979, 1983, 2023; V.F. Sidorchuk et al., 1980; G.G. Boldyrev 1985-1993). It was found that the specific cohesion characteristics for low-moisture soils are about three times greater than for moist soils. The characteristic of the angle of internal friction changes insignificantly. For low-moisture soils, the characteristic of the angle of internal friction is 1-2 degrees higher than that of moist soils (Table 3) [15, 16, etc.].

Table 3. Data on the results of laboratory tests of strength properties of macroporous subsidence soils

Engineering-geological elements	Strength properties of soils c and ϕ	Values of strength properties of loess subsidence soils c , kPa; ϕ , deg.	
		low-moisture	wet
EGE-1	c	42	10
	ϕ	24	22
EGE -2	c	38	14
	ϕ	23	21
EGE -3	c	25	-
	ϕ	22	-
EGE -4	c	-	-
	ϕ	-	-

Table 4. Results of studies of relative subsidence \mathcal{E}_{sl} under pressure on soil samples

BASE soil	Design thickness of EGE, m	Elementary layer thickness h_i , m	Distance of sampling from the ground surface, m	Relative subsidence \mathcal{E}_{sl} , at pressure p , kPa						Initial subsidence pressure P_s , kPa
				20	60	100	140	200	250	
Hard, hummocky, macroporous loam EGE-1	10,4	2,7	-2,7	0,000	0,013	0,027	0,034	0,052	0,056	65
		2,7	-5,4	0,000	0,011	0,024	0,030	0,046	0,050	65
		2,7	-8,1	0,000	0,010	0,021	0,027	0,040	0,045	-
		2,6	-10,7	0,000	-	-	0,025	-	0,042	-
Hard, semi-hard, dark brown loam EGE-2	2,2	0,7	-11,4	0,000	0,010	0,013	0,017	0,021	0,023	-
		0,7	-12,1	0,000	0,011	0,012	0,015	0,019	0,021	-
		0,8	-12,9	0,000	0,011	0,012	-	0,015	0,013	-
tight plastic loam, yellowish brown EGE-3	7,3	1,8	-14,7	-	-	0,008	0,010	0,010	0,010	-
		1,8	-16,5	0,000	0,000	0,000	0,000	0,012	0,000	-
		1,8	-18,3	-	-	-	-	-	-	-
		1,9	-20,2	-	-	-	-	-	-	-

The subsidence properties such as relative subsidence ε_{sl} and initial subsidence pressure p_{sl} were determined in laboratory conditions in accordance with the requirements of GOST 23161-2012 [12]. The values of relative subsidence were established by the “two curves” method which implies testing twin specimens in compression devices taking into account the pressure from own weight of the soil and the pressure transmitted by the foundation sole at the considered depth. The values of the initial subsidence pressure parameter p_{sl} , according to the requirements of regulatory documents, were assumed to be equal to the pressure on the soil sample, at which the relative subsidence ε_{sl} was $\varepsilon_{sl} = 0.01$ (Table 4) [4, 17].

ESTIMATION OF SOIL CONDITIONS TYPE IN TERMS OF SUBSIDENCE

To evaluate the type of ground conditions in terms of subsidence of the construction site under consideration, we plot the stress variation from the soil self-weight σ_{zg} along the depth of the subsidence stratum, taking into account its engineering-geological structure (Fig. 1).

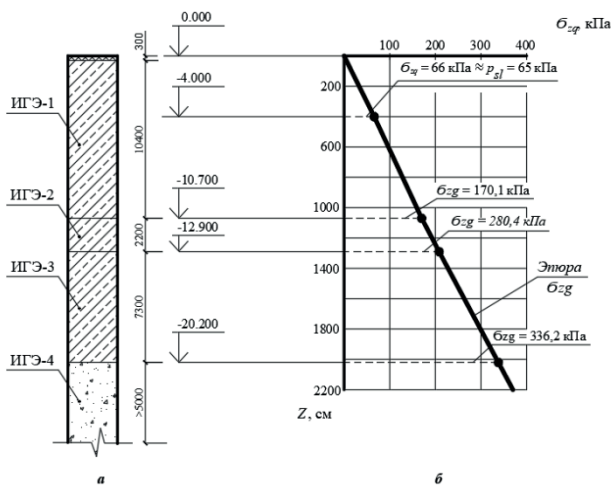


Figure 1. Schematic diagram for determining the type of ground conditions by subsidence for macroporous soils: a - geological column; b - stress distribution diagram from own weight of the soil σ_{zq}

For this purpose, we previously calculate [4]:

- $Z = 2.7 \text{ m}, \sigma_{zg} = 15.9 \times 2.7 = 42.92 \text{ kPa};$
- $Z = 5.4 \text{ m}, \sigma_{zg} = 15.9 \times 5.4 = 85.86 \text{ kPa};$
- $Z = 8.1 \text{ m}, \sigma_{zg} = 15.9 \times 8.1 = 128.79 \text{ kPa};$
- $Z = 10.7 \text{ m}, \sigma_{zg} = 15.9 \times 10.7 = 170.13 \text{ kPa};$
- $Z = 11.4 \text{ m}, \sigma_{zg} = 170.13 + (17.0 \times 0.7) = 182.03 \text{ kPa};$
- $Z = 12.1 \text{ m}, \sigma_{zg} = 182.03 + (17.0 \times 0.7) = 194.83 \text{ kPa};$
- $Z = 12.9 \text{ m}, \sigma_{zg} = 194.83 + (17.0 \times 0.8) = 208.43 \text{ kPa};$
- $Z = 14.7 \text{ m}, \sigma_{zg} = 208.43 + (17.5 \times 1.8) = 239.93 \text{ kPa};$
- $Z = 16.5 \text{ m}, \sigma_{zg} = 239.93 + (17.5 \times 1.8) = 271.43 \text{ kPa};$
- $Z = 18.3 \text{ m}, \sigma_{zg} = 271.43 + (17.5 \times 1.8) = 302.93 \text{ kPa};$
- $Z = 20.2 \text{ m}, \sigma_{zg} = 302.93 + (17.5 \times 1.9) = 336.18 \text{ kPa}$

Using the graph (Fig. 1), we can find the depth where the condition $\sigma_{zg} \approx p_{sl}$ is fulfilled, i.e., σ_{zg} is the stress from own weight of the soil; p_{sl} is the initial subsidence pressure. This condition is fulfilled at the depth $z = 4 \text{ m}$, where $\sigma_{zg} = 66 \text{ kPa} \approx p_{sl} = 65 \text{ kPa}$ as shown Fig. 1 and Table 4. To determine the subsidence from own weight of soil S_{sl} , we conventionally divide the subsidence stratum into layers 2.7-2.8 m thick for EGE-1 and 0.7-0.8 m thick for EGE-2. In this case, the subsidence S_{sl} within the subsidence strata is calculated starting from the depth $z = 4 \text{ m}$, where the stress from own weight of the soil σ_{zg} is equal to the initial subsidence pressure p_{sl} ($\sigma_{zg} = 66 \text{ kPa} \approx p_{sl} = 65 \text{ kPa}$). For the soil strata of tight plastic loam (EGE-3), lying below EGE-2, the breakdown into separate layers is not performed, as the considered thickness of tight plastic loam (EGE-3) practically does not possess subsidence properties and has permissible limits of relative subsidence ε_{sl} . Using the data of Table 4 we plot the dependence of relative subsidence ε_{sl} on the applied external pressure p on the soil (Fig. 2): $\varepsilon_{sl} = f(p)$. All initial data for calculations are summarized in Table 5

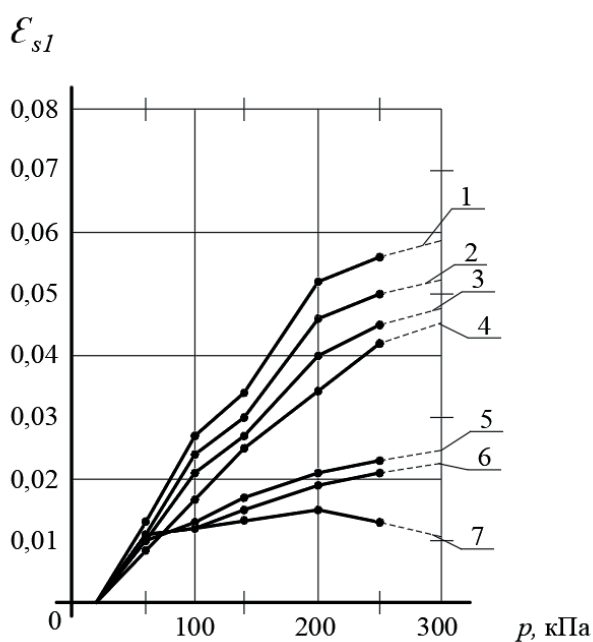


Figure 2. Relative ground subsidence ϵ_{sl} depending on the external applied pressure p : 1...4 - respectively, for EGE-1 soil at -2.7, -5.4, -8.1 and -10.7 m from the ground surface; 5...7 - respectively, for EGE-2 soil at 11.4, 12.1 and 12.9 m from the ground surface.

Table 5. Relative subsidence ϵ_{sl} , at acting stress caused by own weight of the soil $\bar{\sigma}_{zq}$

Soils	Distance to the bottom of the layer under consideration from the ground surface, m	Stresses $\bar{\sigma}_{zq}$ at the base elevation of the layer under consideration, kPa	Relative subsidence ϵ_{sl} at acting stress $\bar{\sigma}_{zq}$
EGE-1	-2,7	42,9	0,012
	-5,4	85,8	0,020
	-8,1	128,8	0,025
	-10,7	170,1	0,030
EGE -2	-11,4	182,0	0,020
	-12,1	194,8	0,017
	-12,9	208,4	0,014

The expected soil subsidence from the action of its own weight S_{sl} (cm) within the subsidence strata is determined from the condition (Krutov V.I. et al., 2013; Polishchuk A.I., Marinichev M.B., 2023):

$$S_{sl} = \sum \epsilon_{sl,i} h_i K_{sl,i} = 0.02 \times 270 \times 1 + 0.025 \times 270 \times 1 + 0.03 \times 260 \times 1 + 0.02 \times 70 \times 1 + 0.017 \times$$

$$70 \times 1 + 0.014 \times 80 \times 1 = 5.4 + 6.75 + 7.8 + 1.4 + 1.19 + 1.12 = 23.7 \text{ cm,}$$

where, n is the number of layers into which the subsidence stratum is divided;

$\epsilon_{sl,i}$ is relative subsidence, determined for each i^{th} layer of the subsidence stratum at the acting stress ($\sigma_{zg} + \sigma_{zr}$);

h_i is the thickness of the considered i^{th} layer of soil, m;

$K_{sl,i}$ is the coefficient of operating conditions of the base.

Thus, it is established that, there are layers of macroporous soil (loam) with total thickness $z = 12,9 - 4,0 = 8,9$ meters within the depth where the condition $\sigma_{zg} > p_{sl}$ fulfills. The subsidence of the considered soil thickness caused by the action of its own weight is more than 5 cm ($S_{sl} = 23.7$ cm). Consequently, the ground conditions of the site under consideration belong to the **second type of subsidence**.

JUSTIFICATION OF PILE TYPE AND LENGTH

For the buildings to be constructed on pile foundations, we accept **prefabricated reinforced concrete prismatic piles** with a cross-section of 300 x 300 mm, which are sunk into the ground ready-made from the bottom of the excavation [2, 4, 18]. This is because of the developed material and technical resources in the construction area (Chechen Republic), where driven reinforced concrete piles will be produced in the required volume. Since the base of the construction site under consideration is composed of macroporous hard loams, the piles should be driven into such soils by means of leader holes, the cross-sectional area of which should be 15-20% smaller than the cross-sectional area of prismatic piles. It is recommended that the depth of the leader wells is approximately 10.5-11.0 m from the surface of the foundation. Within this depth lies the EGE-1 (upper from the base surface). The bearing layer for factory-made prismatic piles is recommended to be hard, semi-hard, dark brown loam, which is part

of EGE-2. The depth of immersion of the lower end of prismatic piles into the bearing layer should be at least 1.0 m in accordance with Table 1.

EXPERIMENTAL AND NUMERICAL DATA ON BEARING CAPACITY OF DRIVEN REINFORCED CONCRETE PILES IN SUBSIDENCE SOILS

The bearing capacity of the considered driven reinforced concrete piles was determined **experimentally** based on the results of **field tests** by static push-in load. Static tests of full-scale piles were carried out in macroporous subsidence soils of natural composition (**low-moisture**) and on pre-wetted (**wet**) soils in accordance with the requirements of Russian standards (GOST 30672-2019, GOST 5686-2020, SP.24.13330.2021, etc.) [19, 20, 21]. In the experiments, driven reinforced concrete prismatic piles of 10 m length and 30x30 cm cross-section were used. The load on the natural piles was transferred by a hydraulic jack with a manual pumping station providing the required operating pressure. The displacements of the test piles were measured by deflection meters.

According to SP 22.13330.2016 (c. 7.3. 5) [13], the bearing capacity of the pile (partial value of the ultimate resistance) F_u under push-in load was assumed to be the load under the influence of which the tested pile received a settlement $S = \xi S_{u,mt}$. ξ is a factor equal to 0.2 if the pile was tested at a conditional stabilization equal to 0.1 mm in 1 hour, if sandy soils and clay soils of solid consistency were under its lower end. $S_{u,mt}$ is the limit value of the mean foundation settlement of the designed building, which is set according to the instructions of the design organization. In the considered case, the value of $S_{u,mt}$ was accepted equal to 12 cm (SP 22.13330.2016). Based on the above formula, the settlement S corresponding to the bearing capacity (ultimate resistance) of the pile F_u at natural moisture content was $S = 0.2 \times 12 = 2.4$ cm (24 mm). The experimental results are pre-

sented in the form of graphs showing the dependences of pile settlements on external load (presented below).

To evaluate the performance of prefabricated reinforced concrete piles in macroporous subsidence soils of the second type, the authors simultaneously carried out numerical studies using the Midas FEA NX software. At the same time, the influence of soaking of the foundation soils (e.g., emergency soaking) on the bearing capacity and settlement of piles, as well as on the development of non-uniform deformations of pile foundations was revealed.

To simulate the loading (“performance”) of soils in the base, the model of hardening soil at small deformations (HS small) was used [22]. This model accounts for the relation of soil stiffness and strength to stress and strain, as well as its over consolidation during load history. This allows for more accurate modeling of its nonlinear deformation under loads. The discussed model provides a correct description of cyclic loading and pore pressure development under undrained conditions, which is important for complex engineering problems. A linear-elastic model with its stiffness characteristics was used for the pile material. Soaking of the subsidence soil was taken into account in the modeling by lowering its strength and deformation characteristics (Figs. 3, 4).

The investigation results of driven reinforced concrete piles' performance in low-moisture and wet subsidence soils are presented in Fig. 5. It is established that in low-moisture and wet (soaking wet) loess soils, the pile settlements recorded during field tests are much smaller compared to the settlements obtained by numerical modeling.

For example, the pile settlement is 4.5 mm under an external load of 140 tf for low-moisture soils, while the pile settlement obtained by numerical modeling under the same load of 140 tf is much larger and amounts to 15.0 mm. In wet subsidence soils, the same trend is also observed. With an external load of 100 tf, the pile settlement is 5.5 mm, while in the case of numerical modeling, the pile settlement at the same load in wet soil is 12.5 mm. According to the results of field static tests, a load

of 100 tf was taken as the bearing capacity of the pile in wet (soaking wet) macroporous soils. The pattern of the resulting graph indicates that the actual bearing capacity of the pile was not established due to the limitation of the maximum load in the test system used. At the same time, a value of 145 tf was found to be the bearing capacity of the pile according to the results of numerical modeling (at 24 mm settlement) as shown in Fig. 5. Due to the idealized conditions of numerical simulation, as well as the discreteness of the problem to be solved, compiled for a single pile, the relationship between settlement and external load after the first iteration, as a rule, has a di-

vergence from the natural plot and does not allow to accept initial stiffnesses for modeling a larger-sized pile group. The applied principle of iterative refinement of strength and shear properties at the pile-soil contact continues until the shape of the load-displacement branches approximates the experimental data. Perfect convergence is achieved with great difficulty, since the full-scale plot incorporates and displays a set of nonlinear processes. The description of these processes is not possible with simplified models that imply an inseparable connection between the pile and the soil during loading [25].

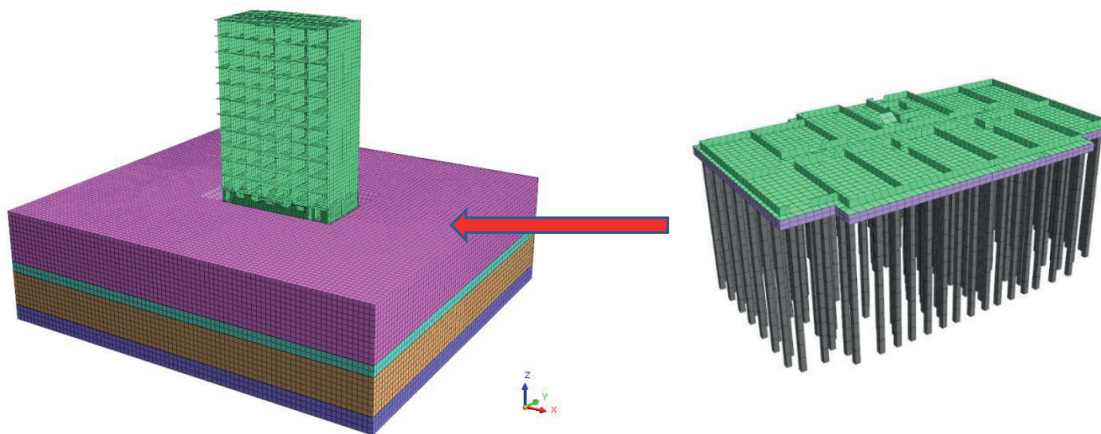


Figure 3. Basement-foundation-structure system with separation of the considered pile foundation (right)

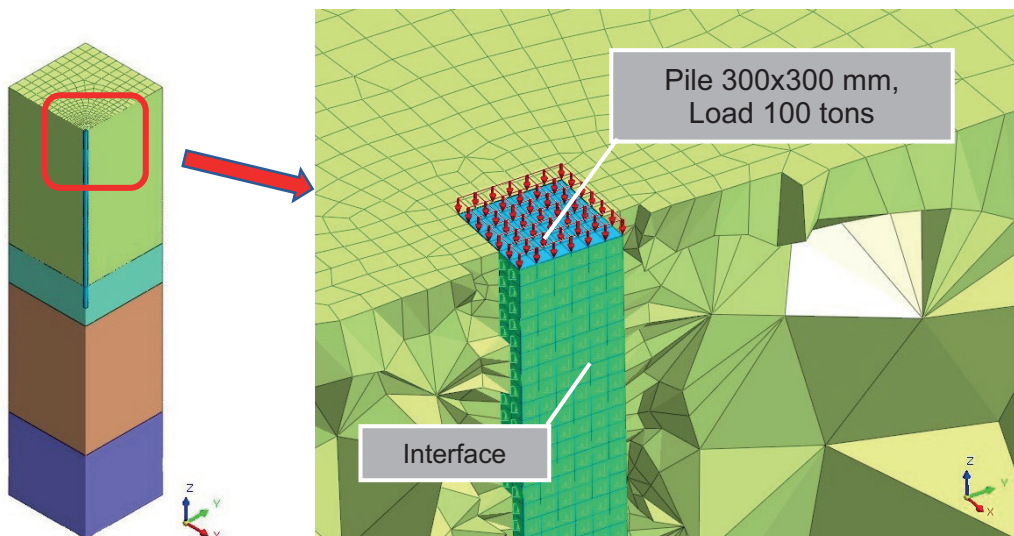


Figure 4. Calculation model of a 30x30 cm pile 10 m in length consisting of solid elements in the given engineering-geological conditions

Fig. 5 shows plots of pile settlement-load dependence for iteratively refined interface properties. Ultimately, a certain convergence of the results was achieved, which allows the synthesized graph to be applied in finite element analysis of the whole system. At the same time, it accounts for the varying properties of the base soils in the manifestation of subsidence properties for loess subsidence soils of the second type of subsidence.

As a result, after the calculations with regard to the verified stiffnesses, the deformations of the system are obtained. They show a high convergence with the results of geotechnical monitoring and can be used for predicting the settlement of single piles on loess macroporous subsidence soils of the second type of subsidence, considering their possible soaking.

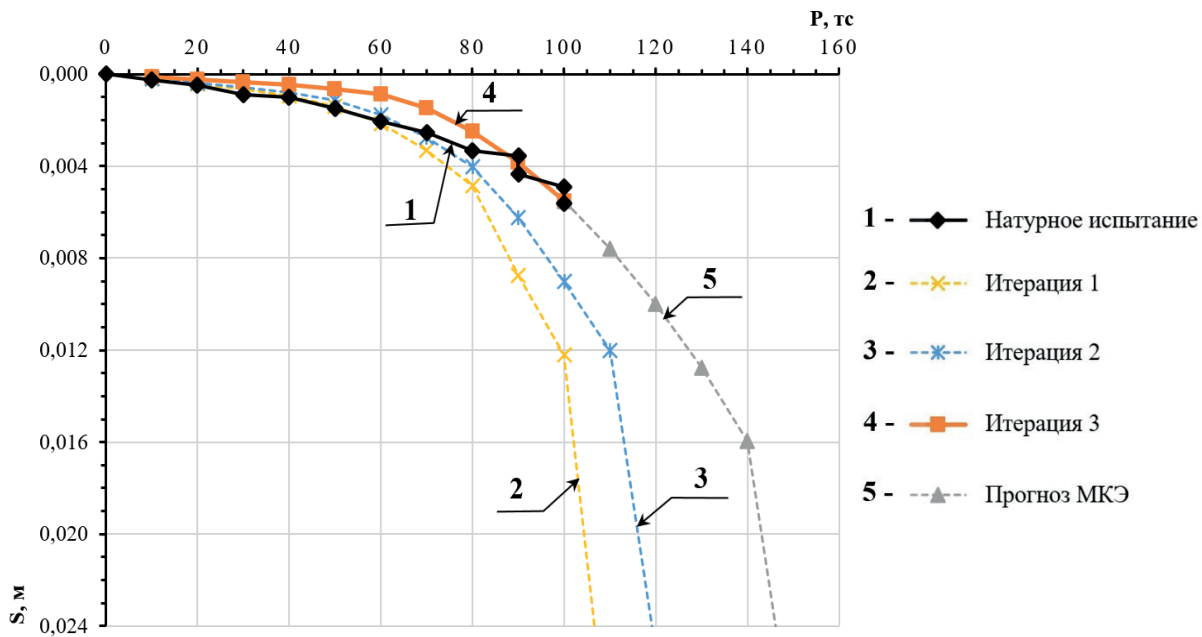


Figure 5. Sequential approximation of the calculated load-settlement diagram to the actual dependence obtained from field tests of a single 30x30 cm pile 10 m length at a construction site made of wet macroporous soils

Thus, the correct analysis of ground conditions of the planned construction, the rules for selecting the structural solution of piles for multi-storey civil buildings, as well as the peculiarities of finite element analysis allow us to justify the main stages of designing pile foundations on macroporous subsidence soils of the second type of subsidence, considering the possible soaking of the compressible thickness of the base.

REFERENCES

1. **Krutov V.I., Kovalev A.S., Kovalev V.A.** Design and construction of bases and foundations on subsidence soils. - Moscow: ASV Publishing House, 2013. - 544 p.
2. **Geotechnical Engineering Handbook.** Bases, foundations and underground structures: 3rd edition, supplemented and revised / Under the general editorship of **V.A. Ilyichev and R.A. Mangushev.** - Moscow: Publishing house ASV, 2023. - 1084 p.
3. **Abelev Y.M., Abelev M.Y.** Fundamentals of design and construction on subsidence macroporous soils. 3rd ed. revision and supplement. - Moscow: Stroyizdat, 1979. - 271 p.
4. **Polischuk A.I., Marinichev M.B.** Bases and foundations, underground structures; ed. by A.I. Polishchuk. 3rd ed. revision and add. - M.: Publishing house ASV, 2023. - 558 p.

5. **Polishchuk A.I.** Analysis of ground conditions of construction in the design of buildings: Scientific and practical manual. -Moscow: Publishing house ASV, 2016. - 104 p.
6. **GOST 12071-2000.** Sampling, packing, transportation and keeping of samples. – Moscow: 2001.
7. **Mangushev R.A., Usmanov R.A.** Bases and Foundations. Solution of practical problems: Textbook. -2nd ed. ster. SPb.: Publishing “Lan”, 2018. - 172 p.
8. **Mangushev R.A., Osokin A.I., Usmanov R.A.** Arrangement and reconstruction of bases and foundations on structurally unstable soils / Edited by R.A. Mangushev: Monograph. -Saint Peterburg: Publishing “Lan”, 2018. - 460 p.
9. **GOST 5180-2015.** Soils. Laboratory methods for determination of physical characteristics. – Moscow: 2016.
10. **Ilyichev V.A., Mangushev R.A.** Geotechnical Engineering Handbook. Bases, foundations and underground structures. -Moscow: ASV Publishing House, 2014. - 728 p.
11. **GOST 12248.4-2000.** Soils. Determination of deformation parameters by compression testing. – Moscow: 2003.
12. **GOST 23161-2012.** Soils. Method of laboratory determination of subsiding characteristics. – Moscow: 2013.
13. **SP 22.13330.2016.** Soil bases of buildings and structures. Updated version of SNIIP 2.02.01-83*. – Moscow: 2017.
14. **GOST 20522-2012.** Soils. Statistical treatment of the test results. – Moscow: 2012.
15. **GOST 12248-2020.** Soils. Determination of strength parameters by shear strength testing. – Moscow: 2020.
16. **Abelev M.Yu.** Peculiarities of construction on loess subsidence soaking soils. - Moscow: Publishing house ASV, 2023. -144 p.
17. Fundamentals of calculation and design of foundations for multi-storey, high-rise and unique buildings: scientific and practical manual / **M.B. Marinichev, O.Y. Yeschenko, V.A. Demchenko, I.G. Tkachev.** - Krasnodar: KubGAU, 2022. - 224 p.
18. **Mangushev R.A., Osokin A.I., Konyushkov V.V., Diakonov I.P., Lanko S.V.** Design of foundations and underground structures (textbook and practical manual). Edited by Corr. of RAACS, Dr. of Technical Sciences, Professor R.A. Mangushev. -Moscow: ASV Publishing House, 2021. - 632 p.
19. **GOST 30672-2019.** Soils. Field testing. General requirements. – Moscow: 2019.
20. **GOST 5686-2020.** Soils. Field test methods by piles. –Moscow: 2020.
21. **SP 24.13330.2021.** Pile foundations. Updated version of SNIIP 2.02.03.85. – Moscow: 2021.
22. **Marinichev M.B.** Foundations of multi-storey and high-rise buildings in special conditions of the South of Russia : Cand. Doctor of technical sciences : 2.1.2 / M.B. Marinichev ; KubGAU (Krasnodar). - Saint-Petersburg : SPBGASU, 2023. - 355 p.
23. **Marinichev M.B.** Compensation of uneven compressibility of the base by the foundation stiffness (at the ground conditions of Krasnodar city and region): Avtoref. dissertation cand. techn. sciences - Volgograd, 2004. - 24 p.
24. **Marinichev M.B.** Implementation of non-standard design solutions in high-rise construction using modern drilling technologies. Polythematic network electronic scientific journal of Kuban State Agrarian University. - 2009. - no. 54. - Pp. 1-8.
25. **Marinichev, M.B.** Research of bored hanging piles in the foundations of multistory and high-rise buildings: Monograph / M.B. Marinichev. - Krasnodar : KubGAU : Prosveshchenie-Yug, 2022. - 155 p. ISBN 978-5-93491-917-8.

СПИСОК ЛИТЕРАТУРЫ

1. **Крутов В.И., Ковалев А.С., Ковалев В.А.** Проектирование и устройство оснований и фундаментов на просадочных грунтах. – М.: Изд-во АСВ, 2013. – 544 с.

2. Справочник геотехника. Основания, фундаменты и подземные сооружения: 3-е издание, дополненное и переработанное / Под общей ред. **В.А. Ильичева и Р.А. Мангушева**. – М.: Изд-во АСВ, 2023. – 1084 с.
3. **Абелев Ю.М., Абелев М.Ю.** Основы проектирования и строительства на просадочных макропористых грунтах. 3-е изд. перераб. и доп. – М.: Стройиздат, 1979. – 271 с.
4. **Полищук А.И., Мариничев М.Б.** Основания и фундаменты, подземные сооружения; под. ред. А.И. Полищука. 3-е изд. перераб. и доп. – М.: Изд-во АСВ, 2023. – 558 С.
5. **Полищук А.И.** Анализ грунтовых условий строительства при проектировании зданий: Научно-практическое пособие. – М.: Изд-во АСВ, 2016. – 104 с.
6. **ГОСТ 12071-2000.** Грунты. Отбор, упаковка, транспортирование и хранение оборудования. – М.: 2001.
7. **Мангушев Р.А., Усманов Р.А.** Основания и фундаменты. Решение практических задач: Учебное пособие. -2-е изд. стер. СПб.: Изд-во «Лань», 2018. – 172 с.
8. **Мангушев Р.А., Осокин А.И., Усманов Р.А.** Устройство и реконструкция оснований и фундаментов на структурно-неустойчивых грунтах / Под ред. Р.А. Мангушева: Монография. –СПб.: Изд-во «Лань», 2018. – 460 с.
9. **ГОСТ 5180-2015.** Грунты. Методы лабораторного определения физических характеристик. – М.: 2016.
10. **Ильичев В.А., Мангушев Р.А.** Справочник геотехника. Основания, фундаменты и подземные сооружения. –М.: Изд-во АСВ, 2014. – 728 с.
11. **ГОСТ 12248.4-2000.** Грунты. Определение характеристик деформируемости методом компрессионного сжатия. – М.: 2003.
12. **ГОСТ 23161-2012.** Межгосударственный стандарт. Метод лабораторного определения характеристик просадочности. – М.: 2013.
13. **СП 22.13330.2016.** Основания зданий и сооружений. Актуализированная редакция СНиП 2.02.01-83*. – М.: 2017.
14. **ГОСТ 20522-2012.** Грунты. Методы статистической обработки результатов испытаний. – М.: 2012.
15. **ГОСТ 12248-2020.** Грунты. Определение характеристик прочности методом одноплоскостного среза. – М.: 2020.
16. **Абелев М.Ю.** Особенности строительства на лессовых просадочных при замачивании грунтах. – М.: Изд-во АСВ, 2023. –144 с.
17. Основы расчета и конструирования фундаментов многоэтажных, высотных и уникальных зданий: научно-практическое пособие / **М.Б. Мариничев, О.Ю. Ещенко, В.А. Демченко, И.Г. Ткачев**. – Краснодар: КубГАУ, 2022. – 224 с.
18. **Мангушев Р.А., Осокин А.И., Конюшков В.В., Дьяконов И.П., Ланько С.В.** Проектирование оснований фундаментов и подземных сооружений (учебное и практическое пособие). Под ред. чл. корр. РААСН, д-ра техн. наук, профессора Р.А. Мангушева. –М.: Изд-во АСВ, 2021. – 632 с.
19. **ГОСТ 30672-2019.** Межгосударственный стандарт. Грунты. Полевые испытания. Общие требования. – М.: 2019.
20. **ГОСТ 5686-2020.** Грунты. Методы полевых испытаний сваями. –М.: 2020.
21. **СП 24.13330.2021.** Свайные фундаменты. Актуализированная редакция СНиП 2.02.03.85. – М.: 2021.
22. **Мариничев М. Б.** Фундаменты многоэтажных и высотных зданий в особых условиях Юга России: дис. ... докт. техн. наук : 2.1.2 / М.Б. Мариничев ; КубГАУ (Краснодар). – Санкт-Петербург : СПбГАСУ, 2023. – 355 с.
23. **Мариничев М.Б.** Компенсация неравномерной сжимаемости основания жесткостью фундамента (на примере грунто-

вых условий г. Краснодара и края): Автореф. диссертации канд. техн. наук – Волгоград, 2004. – 24 с.

24. **Мариничев М.Б.** Реализация нестандартных конструктивных решений в высотном строительстве на основе использования современных буровых технологий. Политематический сетевой электронный научный журнал Кубанского

государственного аграрного университета. – 2009. – № 54. – С. 1–8.

25. **Мариничев М.Б.** Исследование работы буровых висячих свай в составе фундаментов многоэтажных и высотных зданий: Монография / М. Б. Мариничев. – Краснодар : КубГАУ : Просвещение - Юг, 2022. – 155 с. ISBN 978-5-93491-917-8.

Maxim Borisovich Marinichev, Doctor of Technical Sciences, Professor, I.T. Trubilin Kuban State Agrarian University (KubSAU), Address: 13 Kalinina Street, Krasnodar, 350044, Russia, e-mail: marinichev@list.ru

Максим Борисович Мариничев, д-р техн. наук, профессор кафедры «Основания и фундаменты», Кубанский государственный аграрный университет имени И.Т. Трубилина (КубГАУ), Адрес: д. 13, улица им. Калинина, г. Краснодар 350044, Россия, e-mail: marinichev@list.ru

Anatoly Ivanovich Polishchuk, Doctor of Technical Sciences, Professor, I.T. Trubilin Kuban State Agrarian University (KubSAU), Address: 13 Kalinina Street, Krasnodar, 350044, Russia, e-mail: ofpai@mail.ru

Анатолий Иванович Полищук, д-р техн. наук, профессор кафедры «Основания и фундаменты», Кубанский государственный аграрный университет имени И.Т. Трубилина (КубГАУ), Адрес: д. 13, улица им. Калинина, г. Краснодар 350044, Россия, e-mail: ofpai@mail.ru

Nadezhda Sergeevna Nikitina, Candidate of Technical Sciences, Professor, Moscow State University of Civil Engineering (NRU MGSU), Address: 26, Yaroslavskoye Highway, Moscow, 129337, Russia, e-mail: NikitinaNS@mgsu.ru

Надежда Сергеевна Никитина, канд. техн. наук, профессор кафедры «Механика грунтов и геотехника», Московский государственный строительный университет (НИУ МГСУ), Адрес: д. 26, Ярославское ш., г. Москва, 129337, Россия, e-mail: NikitinaNS@mgsu.ru