PANEVĖŽIO KOLEGIJA ISSN 2029-1280, eISSN 2669-0071. Taikomieji tyrimai studijose ir praktikoje – Applied Research in Studies and Practice, 2025, 21.

RESEARCH OF BEARING CAPACITY OF PILE PRESSED FOUNDATIONS IN DOUBLE-LAYER SOIL

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Annotation. Homogeneous soil is rarely found in nature. Most often, soil consists of layers with different properties. Pile foundations are used to transfer structural loads to solid soil layers. This article examines the dependence of the bearing capacity of pile foundations on the depth of embedment and the diameter of the pile in the case of two-layer soil.
Keywords: pile foundations, double-layer soil, bearing capacity

INTRODUCTION

The article presents the results of calculations of the bearing capacity of squeezed piles. This type of pile is characterized by the fact that during embedment, it compacts the soil around it [1, 2]. The study analyzed the influence of the pile diameter and soil properties, specifically its compressive strength, on the bearing capacity.

A previous study [3] analyzed the bearing capacity of squeezed piles in homogeneous soil. This paper presents the results obtained by analyzing the bearing capacity as a function of the embedment depth in two-layer soil. The calculations were performed using the limit state method. The bearing capacity was determined by evaluating the strength of the foundation soil and the strength of the pile material. The design was based on the lower bearing capacity of one of them [4].

When performing the calculations, it was assumed that the pile foot is pressed into the lower soil layer and the bearing capacity of the soil under the pile foot is assessed. It was also decided that the pile would be pressed to a depth of 9 m. The pile is driven into the lower soil layer to a depth of 0.5 m. Thus, most of the pile's side surface (8.5 m) is in contact with the upper soil layer. It is this part that determines the bearing capacity of the pile's side surface.

Methodology for calculating the bearing capacity of the pile base

During the study, the limit bearing capacity of the pile foundation was calculated using the empirical method based on the data of static soil probing. During static probing, the limit bearing capacity $R_{c;m}$ is determined, to which the partial coefficients γ_R (γ_b, γ_s, γ_t) are applied, and the design bearing capacity R_d is found using equation (1) [4]. According to LST EN 1997 – 1:2003 [5], these coefficients depend on the number of tests performed.

$$R_d = R_{c;m}/ \gamma_t; \tag{1}$$

Here $\gamma_t = 1$ is a partial coefficient, which depends on the pile installation method [4].

When carrying out calculations of the load-bearing capacity of the pile base, first the load-bearing capacity of the pile $R_{c;cal}$ is calculated. Then the characteristic value of the load-bearing capacity $R_{c;k}$ is determined and the design value of the load-bearing capacity $R_{c;d}$ is calculated.

The load-bearing capacity R_c of one pile is calculated as the sum of the load-bearing capacity R_b of the foundation under the base of the pile and the load-bearing capacity R_s of the sides of the pile:

$$R_c = R_b+R_s; \tag{2}$$

The bearing capacity of the base under the pile is calculated using equation:

$$R_b = \alpha_b \cdot q_c \cdot A_b; \tag{3}$$

Here q_c is the cone strength of the soil, MPa; α_b – empirical correlation coefficient between q_c and base strength (values were selected from [4]); A_b is the area of pile sole in m^2. Cylindrical piles were investigated in this work.

The bearing capacity of the pile sides is calculated using equation:

$$R_s = \sum (A_{si} \cdot q_{ci} \cdot \alpha_{si}); \tag{4}$$

Here A_{si} is the surface area of the pile sides of the i^{th} soil layer, m^2; q_{ci} is conical strength of the i^{th} soil layer, MPa; α_{si} is empirical coefficient of correlation between q_c and soil friction strength, depending on soil type (values were selected from [4]).

The bearing capacity of the pile is calculated using equation:

$$R_{c,cal} = R_b / \gamma_{Rb} + R_s / \gamma_{Rs}; \tag{5}$$

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Here γ_{Rb} and γ_{Rs} are modelling coefficients that depends on the method of pile installation. In this work, clamped bored piles were investigated, so γ_{Rb} = 1.1 and γ_{Rs} = 1.35 [4].

The characteristic value of the bearing capacity of the pile base is calculated using equation

$$R_{c;k} = min\{(R_{c;m})mean / \varsigma_1; (R_{c;m})min / \varsigma_2\}; \quad (6)$$

Here $(R_{c;m})mean$ is the average value of the bearing capacity of the pile base, N; $(R_{c;m})min$ is the minimum value of the bearing capacity, N; ς_1 and ς_2 are correlation coefficients, the values of which depend on the number of poles tested under static loads.

It was assumed that ς_1 = 1 and ς_2 = 1 (numerical values selected according to [4]) in this work.

The design bearing capacity of the pile is calculated using equation

$$R_{c;d} = R_{c;k} / \gamma_t; \quad (7)$$

In order for the pole foundation to safely withstand the calculated compressive loads (in all cases of safety limit state loads and their combinations), the following inequality must be satisfied [6]:

$$F_{c;d} \leq R_{c;d}; \quad (8)$$

Here $F_{c;d}$ is the calculated value of the representative axial compressive force of the load of the pile or their group, including the weight force of the pile itself or their group (N); $R_{c;d}$ is calculated value of R_c (N); R_c is bearing capacity (N) of the compressive pile foundation.

PILE BEARING CAPACITY DEPENDENCE ON TWO LAYERS OF SOIL

The following conditions were assumed during the calculation of the bearing capacity of the piles:

- The soil into which the pile is pressed consists of two different layers of soil;
- The cross-section of the pile is round;
- The entire pile is fully (100%) pressed into the ground;
- Pile weight is not taken into account;
- The influence of groundwater on the compressive strength of the soil is also not assessed.

The calculations were performed using four different soil types: sand, sandy loam, loam, and clay. During the calculations, the type of the upper soil layer was changed. The compressive strength of each soil type was also changed. The soil characteristics are presented in Table 1.

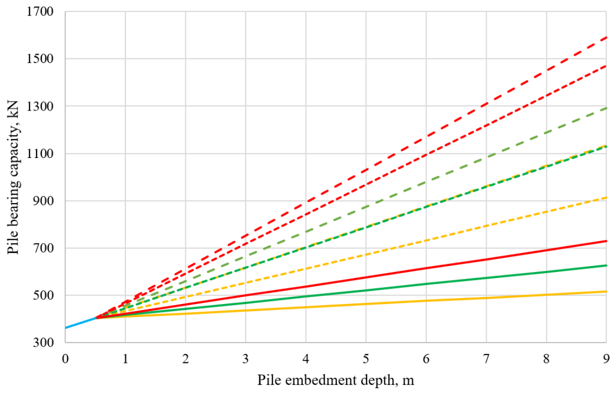
During the research, it was assumed that the pile would be driven to a depth of 9 m. The pile is driven 0.5 m into the lower soil layer, and the remaining part (8.5 m) is driven into the upper layer. Since most of the pile is in contact with the upper soil layer, this soil layer determines the bearing capacity of the pile's side surface. The lower soil layer determines the bearing capacity of the soil under the pile.

Table 1

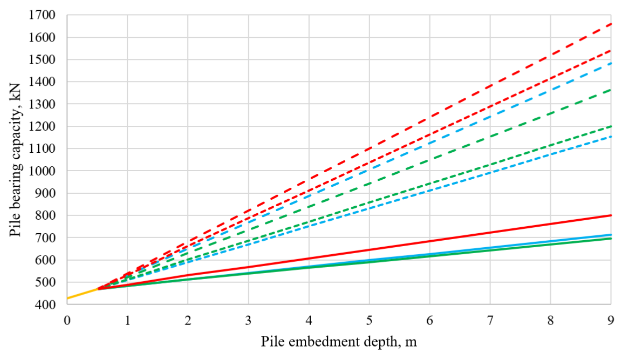
Mechanical characteristics of soils

		Compressive strength q_c, MPa
Sand	Sand (1)	4,1
	Sand (2)	11,3
	Sand (3)	25,0
Sandy loam	Sandy loam (1)	1,9
	Sandy loam (2)	8,59
	Sandy loam (3)	13,29
Loam	Loam (1)	1,5
	Loam (2)	4,9
	Loam (3)	12,7
Clay	Clay (1)	1,1
	Clay (2)	3,6
	Clay (3)	6,7

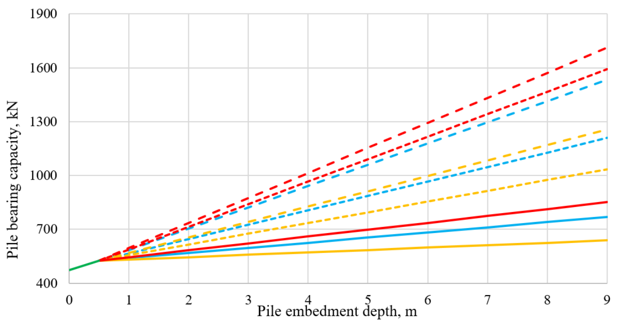
The dependence of the bearing capacity of a pile on the depth of pile insertion in a two-layer soil is shown in Figure 1. The graphs show average values.



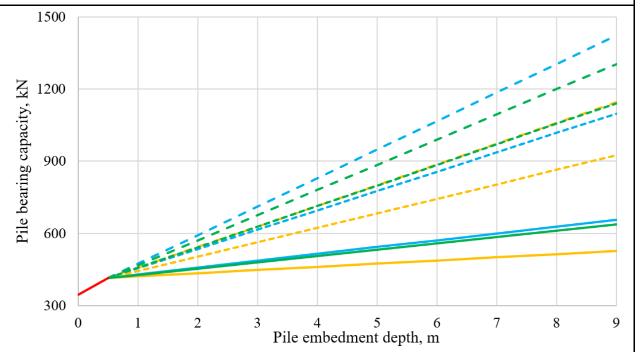
Lower layer: ■ sand (compressive strength 11,3 MPa). Upper layers: ■ sandy loam; ■ loam; ■ clay. Compressive strength of upper layer: ——— sandy loam 1,9 MPa, loam 1,5 MPa, clay 1,1 MPa; ----- sandy loam 8,59 MPa, loam 4,9 MPa, clay 3,6 MPa; - - - sandy loam 13,29 MPa, loam 12,27 MPa, clay 6,7 MPa.



Lower layer: ■ sandy loam (compressive strength 8,59 MPa). Upper layers: ■ sand; ■ loam; ■ clay. Compressive strength of upper layer: ——— sand 4,1 MPa, loam 1,5 MPa, clay 1,1 MPa; ----- sand 11,3 MPa, loam 4,9 MPa, clay 3,6 MPa; - - - sand 25,0 MPa, loam 12,27 MPa, clay 6,7 MPa.



Lower layer: ■ loam (compressive strength 12,27 MPa). Upper layers: ■ sand; ■ sandy loam; ■ clay. Compressive strength of upper layer: ——— sand 4,1 MPa, sandy loam 1,9 MPa, clay 1,1 MPa; ----- sand 11,3 MPa, sandy loam 8,59 MPa, clay 3,6 MPa; - - - sand 25,0 MPa, sandy loam 13,29 MPa, clay 6,7 MPa.



Lower layer: ■ clay (compressive strength 6,7 MPa). Upper layers: ■ sand; ■ sandy loam; ■ loam. Compressive strength of upper layer: ——— sand 4,1 MPa, sandy loam 1,9 MPa, loam 1,5 MPa; ----- sand 11,3 MPa, sandy loam 8,59 MPa, loam 4,9 MPa; - - - sand 25,0 MPa, sandy loam 13,29 MPa, loam 12,27 MPa.

Figure 1.**Pile bearing capacity dependencies on pile embedment depth in double-layer soil (pile diameter is 0,3 m)**

The graphs show the results of bearing capacity calculations when changing the type of the upper soil layer, while the lower soil layer remained the same. The calculation results are presented for a pile diameter of 0.3 meters. It should be noted that the graphs show the bearing capacity values when the pile is fully driven to a depth of 9 m.

The graphs in Figure 1 show the bearing capacity of the soil beneath the pile when the pile penetration depth is 0. The section where the pile penetration depth is between 0 and 0.5 meters shows the bearing capacity of the lower soil layer. In the remaining section, where the pile embedment depth varies from 0.5 to 9 meters, the variation in the bearing capacity of the pile side surface in different types of topsoil is shown for different topsoil compressive strengths.

The results show that the higher the compressive strength of the lower soil layer, the greater the increase in the bearing capacity of the upper soil layers. The results also show that the properties of the lower layer do not affect the gradient of change in the bearing capacity of the upper layer. Only the compressive strength of the layer affects the bearing capacity gradient.

Figure 2 shows the results of bearing capacity calculations in two-layer soil with a pile diameter of 0.4 m for comparison. The results were obtained by taking the maximum compressive strength of each layer.

PANEVĖŽIO KOLEGIJA ISSN 2029-1280, eISSN 2669-0071. Taikomieji tyrimai studijose ir praktikoje – Applied Research in Studies and Practice, 2025, 21.

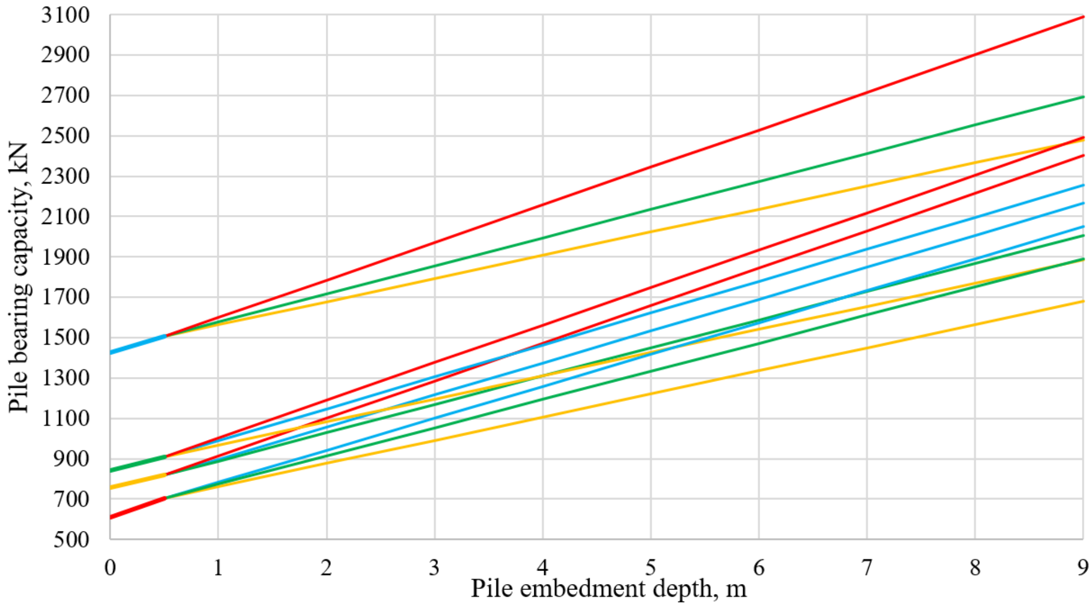
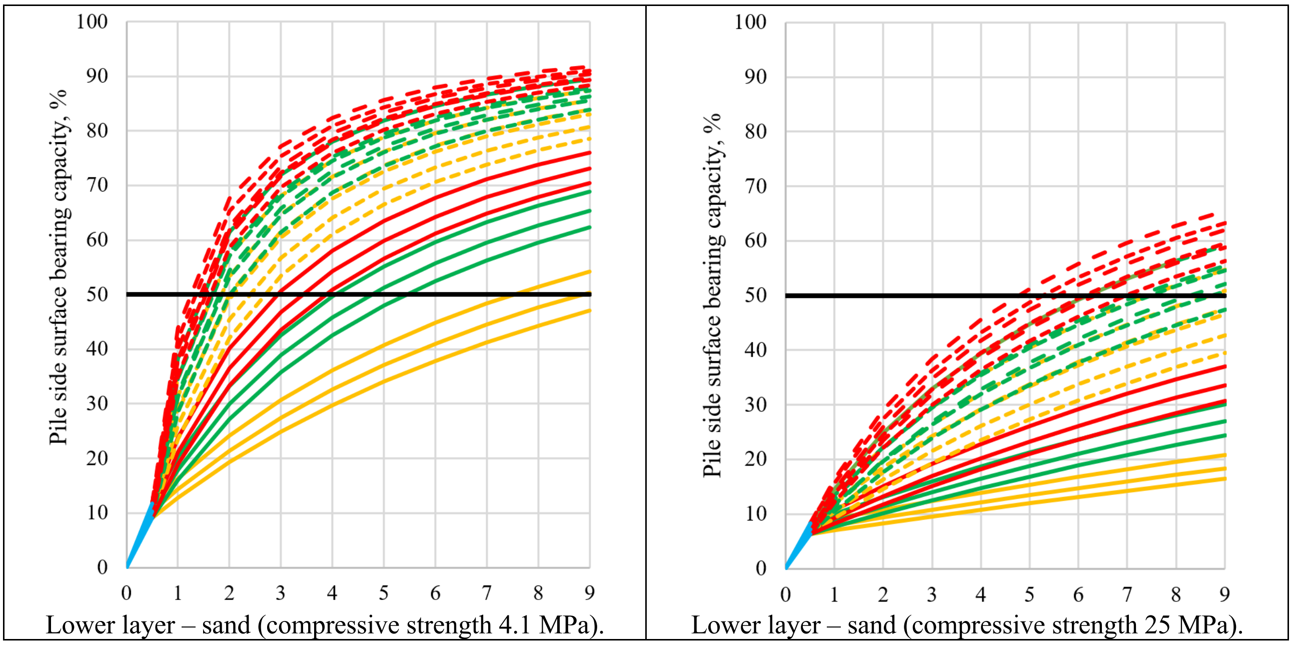


Figure 2. **Dependencies of the bearing capacity of the pile on the embedment depth of pile in double-layer soil, when the pile diameter is 0,4 m (soil layers and their compressice strength: ■ sand (25,0 MPa); ■ sandy loam (13,29 MPa); ■ loam (12,27 MPa); ■ clay (6,7 MPa))**

Comparing the results presented in Figures 1 and 2, it can be seen that when the diameter of the pile increases by about 30 percent, the bearing capacity of the side surface in the lower layer increases by about 70 percent. The bearing capacity under the pile base increases from 70 to 80 percent. The bearing capacity of the side pile surface in the upper soil layer increases from 45 to 50 percent, respectively. The gradient of the change in bearing capacity increases from 30 to 35 percent.

Figure 3 shows the results of the distribution of the bearing capacity of the pile between the pile foot and the pile side surface in two layers of soil. The graphs show the results when the lower soil layer was sand and clay. For comparison, variants with minimum and maximum compressive strength values of the lower soil layer were selected. These graphs show the results for three different pile diameter values.



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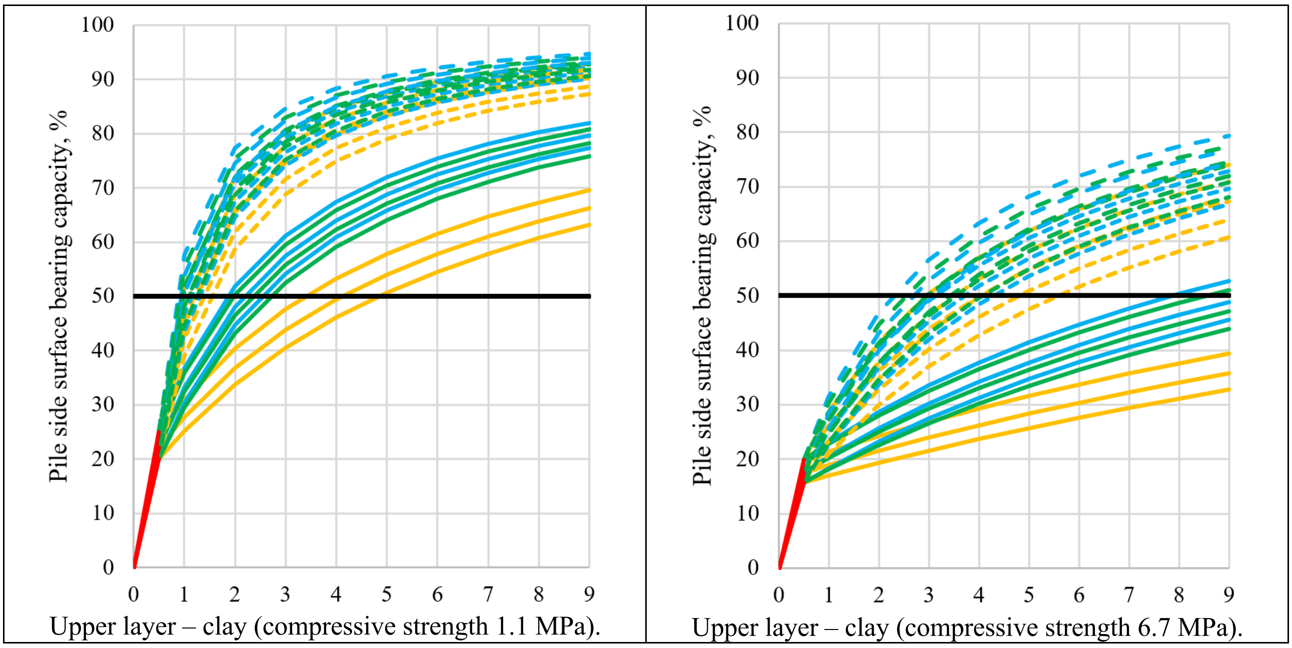

Figure 3. **Dependence of the bearing capacity ratio of the side surface of the pile to the bearing capacity of the pile base on the depth of pile insertion (pile diameter: ── 0,30 m; ----- 0,35 m; - - - 0,40 m; soil: ■ sand; ■ sandy loam; ■ loam; ■ clay)**

The results show that as the compressive strength of the bottom layer increases, a larger portion of the bearing capacity, at the same pile insertion depth, is transferred to the pile tip. As the pile diameter increases, a larger portion of the bearing capacity is transferred to the pile side surface.

Both the compressive strength and the diameter of the pile influence the distribution of bearing capacity between the side surface and the pile toe. As the pile diameter increases, a larger proportion of the bearing capacity is transferred to the side surface of the pile. As the compressive strength of the soil layers increases, the proportion of bearing capacity transferred to the base of the pile also increases.

CONCLUSIONS

1. The greater the compressive strength of the lower soil layer, the greater the increase in the bearing capacity of the upper soil layers
2. The properties of the lower layer do not affect the gradient of the load-bearing capacity of the upper layer.
3. By increasing the diameter of the pile by one third, the bearing capacity of the side surface in the lower soil layer increases by about 70 percent, the bearing capacity under the pile base increases from 70 to 80 percent, and the bearing capacity of the side surface in the upper soil layer increases from 45 to 50 percent.
4. Both the compressive strength and the diameter of the pile influence the distribution of bearing capacity between the side surface and the pile toe. As the pile diameter increases, a larger proportion of the bearing capacity is transferred to the side surface of the pile. As the compressive strength of the soil layers increases, the proportion of bearing capacity transferred to the base of the pile also increases.

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