Budownictwo i Architektura 23(3) 2024, 87-97

DOI: 10.35784/bud-arch.5661
Received: 10.12.2023; Revised: 09.06.2024;
Accepted: 15.06.2024; Available online: 30.09.2024

Orginal Article

Analysis of building foundations on weak soils using FEM

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Abstract: The reinforcement of soil with concrete columns, as well as pile foundations, is commonly used in building construction, particularly in cases where weak soils are present. This paper presents a comparative analysis of the foundation of an engineering structure using two methods: pile foundations and soil reinforcement with concrete columns. While both methods are similar in terms of execution, they differ in their working characteristics and calculation approaches. The structure analysed was a multi-family building consisting of two residential sections connected by an underground garage. Numerical analyses were conducted using the Finite Element Method (FEM). The load-bearing capacity of a single pile was calculated directly from the results of CPTU soundings using the LCPC method. The analysis led to the design of 1,096 concrete columns with a diameter of 300 mm and a total length of 7,485.5 metres, as well as 334 foundation piles with a diameter of 500 mm and a total length of 3,305.5 metres. The difference in concrete volume is approximately 120 m³ in favour of the columns, which constitutes nearly 20% of the total concrete volume. The columns were primarily designed in concrete, which results in additional steel savings, as all foundation piles would require reinforcement.

Keywords: foundation piles, concrete columns, Finite Element Method, flat deformation state, axisymmetric, LCPC

1. Introduction

Foundations are an integral part of every engineering structure. Their form, dimensions, and reinforcement are closely related to ground conditions. In the case of weak-bearing soil, such as organic or plasticised mineral soil, deep foundations or soil reinforcement are required. Reinforcement is usually carried out by introducing vertical concrete inclusions into the underlying soil.

This article presents the results of foundation analysis in two variants: using foundation piles and reinforcing the soil with concrete columns. The calculations were performed as part of a master's thesis. The subject of the analysis was a multi-family building consisting of two housing units connected by an underground garage. The facility will be located in Lublin, in close proximity to the Czerniejówka River. The necessity for deep foundations arose from the presence of uncontrolled embankments in the upper layers of the soil, as well as organic soils in the form of peat and mud, and partially loosened sands. Numerical analyses were conducted using the Finite Element Method (FEM) in the GEO5 and PL-Win programs.

2. FEM in geotechnical modelling

The Finite Element Method is often applied in engineering, including in geotechnical calculations. For complex issues, it becomes an indispensable element of analysis. Depending on the complexity of the task, various methods of geometric modelling are used. The most accurate results can be obtained using three-dimensional (3D) models. Unfortunately, developing 3D models is time-consuming, especially for complex structures, and requires the use of specialised software. Therefore, issues are often simplified to two-dimensional (2D) tasks conducted on representative cross-sections. For the purposes of these analyses, two methods were used. The first is the flat deformation state, while the second is axisymmetry (Fig. 1).

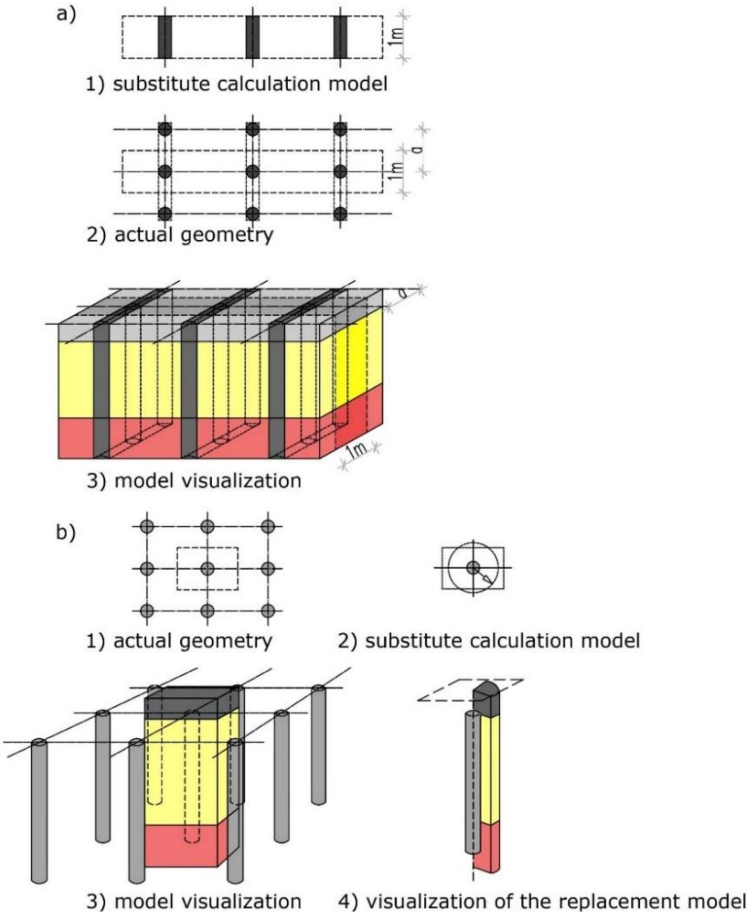

Fig. 1. Assumptions for modelling a) flat deformation state model, b) axisymmetric model (based on [1])

In the flat deformation state, a two-dimensional model is developed with the assumption of calculations for 1 running metre of the cross-section. This is a relatively simple and frequently used method of modelling soil substructures, especially useful for linear objects. Such a model provides an acceptable approximation for the analysis of column or pile foundations only in simple computational cases [1]. Analysing the settlement of the entire structure using the flat deformation state constitutes a simplification.

Axisymmetry is suitable for structures and axially symmetric loads, or those which can be easily transformed into such a form. Therefore, it is often used when calculating piles and columns. The basis for calculations is a flat model, where one of the edges serves as the axis of symmetry, around which the model is computationally 'rotated' by 360 degrees.

Models in the flat state of deformation and axisymmetry were created in the GEO5-MES program. In the flat condition, the cross-section was modelled in the most unfavourable location, while axisymmetry was used to reproduce the operation of individual columns under various soil conditions.

Besides the calculation method, a key aspect is the proper determination of soil parameters and the selection of an appropriate constitutive material model describing its operation. In the analysis, the Coulomb-Mohr failure criterion model was applied. It assumes soil failure when the shear stresses reach a value linearly dependent on the normal stresses in the same plane at any point in the ground [2]. The advantage of this model lies in its simplicity and the use of the assumptions of traditional soil and rock mechanics.

3. Foundation piles and concrete columns

In the field of foundation engineering, numerous methods have been developed. Traditionally, foundations are classified into shallow foundations, which function through bearing pressure at their base (e.g., foundation footings, strip footings, and foundation slabs (Fig. 2a)), and deep foundations (e.g., piles) working through friction on the side surface and bearing pressure at the base (Fig. 2b). In the case of piles, this is a computational simplification, because some parts of the loads are also transferred by the structure atop the piles. Therefore, in more complex analyses, so-called combined foundations, i.e., slab-pile systems (Fig. 2c), are considered. These are a combination of shallow and deep foundations where the piles are monolithically connected to the foundation slab structure [3]. However, the difficulty lies in accurately allocating the scope of load transfer by individual elements. The load from the structure is transferred to the foundation slab and, from there, to the ground between the piles, relying on friction on the side of the pile and reaction at its base.

An increasingly common practice in geotechnical engineering is the use of soil reinforcement with concrete columns, as illustrated in Fig. 2d. The operation principle is similar to a slab-pile foundation, but there is no rigid connection between the inclusions and the shallow foundation. Instead, there is often an additional transmission layer, whose task is to uniformize stresses beneath the foundation. This layer is typically made of cohesionless soils, such as gravel or sand [4]. The thickness depends, among other factors, on the spacing of the columns, load magnitude, and the stiffness and sensitivity of the topping structure. For typical building structures, it usually ranges from about 0.5 to 1.0 metres. Implementing reinforcement in this form leads to the creation of a composite soil, characterized by higher load-bearing capacity and lower settlement than the original soil [1].

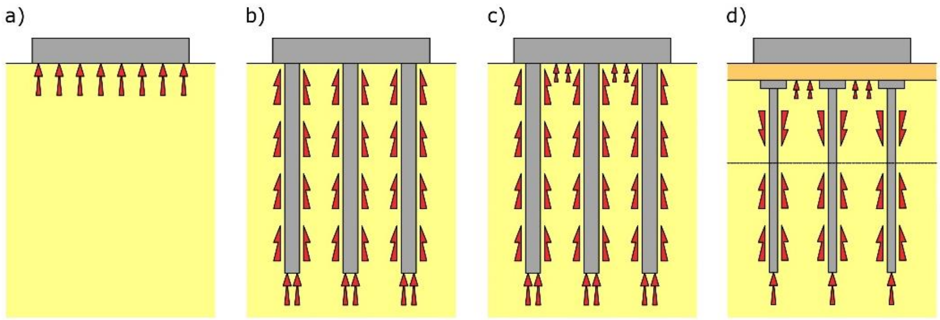

Fig. 2. Various types of foundations: a) slab foundation, b) pile foundation, c) slab-pile foundation, d) soil reinforcement with concrete columns (based on [1])

Pile foundations and soil reinforcement with concrete columns may appear to be similar solutions. Indeed, they are similar in terms of execution, but they differ in their working characteristics and design assumptions. Both piles and columns can be constructed using the same technologies, with identical shapes (often cylindrical or prismatic in the case of prefabricated elements) and materials. In modern construction, almost all of them are made of concrete or reinforced concrete. Commonly used technologies include CFA and FDP or their modifications, as they are fast to execute and relatively cost-effective.

In both piles and columns, friction on the side surface and bearing pressure at the base are utilized to transfer loads to the soil [5]. The main difference, however, lies in the assumption that for pile foundations, the piles are expected to bear the entire load, whereas in the case of columns, the soil between the inclusions is also included to transfer the loads [6].

Reinforcement with columns is most commonly employed in cases where there are no restrictive criteria regarding the settlement of the structure, whereas pile foundations are used when such a necessity arises [7,8]. When considering reinforcement, the effect of reducing the settlement of the entire structure is examined, and this technology is not recommended for very large loads. The scope of applying piles is broader than that of concrete columns [9].

Piles are monolithically connected to the structure with reinforcement, and often intentional provisions are made to enable the transfer of bending moments. However, columns do not have a rigid connection with the foundation [10]. Depending on the design, column heads may be located directly under the foundation or separated by a transmission layer.

Columns typically have smaller diameters compared to piles, but their number is greater, and they are spaced more closely. Column lengths are shorter because they are only slightly embedded in the supporting soil, whereas piles are driven deeper [4].

4. The analysed object and the need for deep foundations

The subject of the analysis was a designed multi-family residential building consisting of two residential parts (B1, B2) with four above-ground floors and one underground floor, connected by an underground garage (G). In the past, the area was built up, resulting in an anthropogenic layer in the form of uncontrolled embankments up to 3.5 meters thick below ground level in the eastern part of the plot [11].

The area is located within the valley of the Czerniejówka River, whose bed forms the eastern boundary of the site. In the valley, organic soils have accumulated in the form of plastic and soft plastic silty muds, loose sandy muds, and peat, which extends over a significant part of the eastern side of the plot. Below the organics, there is a small layer of partially loosened sands, with deeper layers consisting of weathered-rocky material. A representative geotechnical cross-section along with the outline of the proposed foundation is depicted in Fig. 3. The foundation level is planned at an elevation of approximately 170 meters above sea level, where the groundwater table is present. The soil and water conditions are classified as complex, and the structure is categorized as geotechnical category II [12].

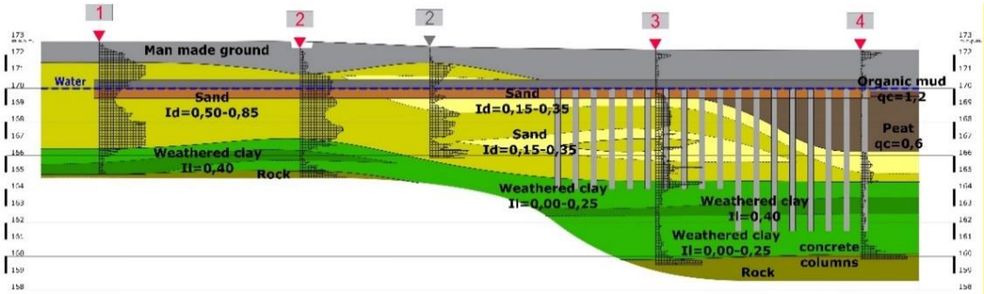

Fig. 3. Geotechnical cross-section with an outline of the foundation (based on [11])

Due to the presence of weak-bearing soils and a high groundwater level, it was necessary to design a deep foundation. In the thesis, the foundation solution was analysed in two variants: pile foundations and soil reinforcement with concrete columns.

Both the columns and piles were designed using FDP (Full Displacement Piles) technology. This is a type of displacement pile. Drilling is carried out without a casing pipe, using a specially designed auger that displaces the soil sideways without extracting the excavated material to the surface, resulting in soil densification. Additional improvement of soil parameters is achieved through concrete, which is injected under pressure through the auger core [13]. A diameter of 500 mm was assumed for the piles and 300 mm for the columns. Piles were driven deeper into the load-bearing soils, reaching the weathered-rocky subsoil, while columns were founded at a shallower depth compared to piles. The considered foundation covered the eastern part of the building (Fig. 4), which constitutes approximately half of the structure's area. The analyses focused only on these portions of the structure.

a) b)

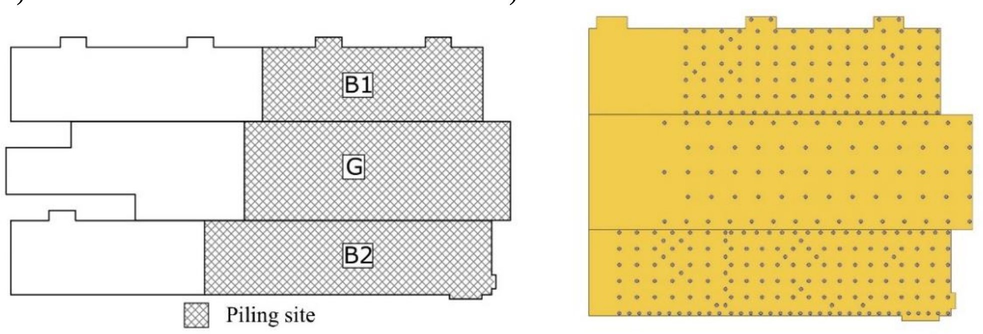

Fig. 4. a) piling area, b) scheme of pile arrangement diagram (PL-Win model)

5. Foundation on foundation piles

The load-bearing capacity of the pile foundations was directly determined from the results of CPTU tests. A total of eight soundings were used for load capacity assessment (two for building B1, three for building B2, and three for the garage). Load capacity calculation methods for piles based on static sounding results mainly differ in the way q_c, q_{csi}, and f_{si} are averaged, as well as the coefficients ψ_1, ψ_2, and ψ_3 [13], and are often dedicated to specific technologies. Due to the significant diversity of values obtained in CPTU tests, the averaging process of q_c and f_s values and adopting representative values, especially in the pile base zone, is crucial. The LCPC method was used in the analyses, in which the representative cone resistance q_c for the pile base is calculated in the settlement zone covering the range of ±1.5 times the pile diameter. Additionally, values that are extremely high, i.e., deviating more than 30% from the average value, are reduced. The bearing capacity of the pile shaft is calculated based on the averaged cone resistance q_c within the designated soil layer, which is then divided by the appropriate coefficient ψ_2. This coefficient depends on the type of soil and the piling technology used.

The distribution of forces on individual piles was determined using the Finite Element Method (FEM). In the PL-Win program, a foundation slab supported by piles was modelled, and stiffness was assumed iteratively for the piles. It was assumed that the entire load from the building is transferred by the pile foundations, completely neglecting the resistance under the foundation slab. The piles were arranged in a rectangular grid with basic spacings of 2.62 x 2.35 m for building B1, 2.26 x 2.33 m for building B2, and 3.42 x 3.56 m for garage G (Fig. 4). Concrete C25/30 was assumed for both the piles and the foundation slab. The maximum force was 790.0 kN under building B1, 680.0 kN under garage G, and 637.6 kN under building B2.

In Tables 1–3, the results of load capacity calculations for piles are presented. The symbols used are as follows: R_c – characteristic pile load-bearing capacity, $R_{c,mean}$ – average pile load-bearing capacity, $R_{c,min}$ – minimum pile load-bearing capacity, R_{ck} – characteristic pile load-bearing capacity based on $R_{c,mean}$ and $R_{c,min}$, R_{cd} – design pile load-bearing capacity. The proposed spacing was considered optimal, aiming for the maximum utilisation of pile capacity, which averaged 90% for piles under building B1, 90% for piles under building B2, and 94% for piles under garage G.

Table. 1. Load capacity of piles under building B1

Test number		Ø	L	R_c	$R_{c,mean}$	$R_{c,min}$	R_{ck}	R_{cd}
		[mm]	[m]	[kN]	[kN]	[kN]	[kN]	[kN]
CPT	3	500	11.5	1404.7	1161.6	918.4	878.0	798.6
CPT	4		11.0	918.43				

Table. 2. Load capacity of piles under garage G

Test number		Ø	L	R_c	$R_{c,mean}$	$R_{c,min}$	R_{ck}	R_{cd}
		[mm]	[m]	[kN]	[kN]	[kN]	[kN]	[kN]
CPT	3		9.5	1185.7				
CPT	7	500	8.5	794.3	973.3	794.3	759.8	690.7
CPT	8		8.5	939.9				

Table. 3. Load capacity of piles under building B2

Test number		Ø [mm]	L [m]	R_c [kN]	$R_{c,mean}$ [kN]	$R_{c,min}$ [kN]	R_{ck} [kN]	R_{cd} [kN]
CPT	7	500	10.0	874.7	861.0	738.0	705.9	641.7
CPT	8		8.5	970.3				
CPT	2A		9.0	738.0				

To analyse the settlement of the entire structure, calculations were carried out in a flat deformation state for the most unfavourable section. For computational optimisation, the model was divided into two parts: building B1 with the left half of garage G (Fig. 5, Fig. 6 on the left) and building B2 with the right half of garage G (Fig. 5, Fig. 6 on the right). The calculations were performed in six phases: '*Existing Terrain*,' '*Excavation*,' '*Pile Installation*,' '*Foundation Slab Construction*,' '*Characteristic Loads*,' and '*Design Loads*.' The interaction between the pile shaft and the subsoil was simulated using contact elements with parameters determined based on the settlement analysis of individual piles.

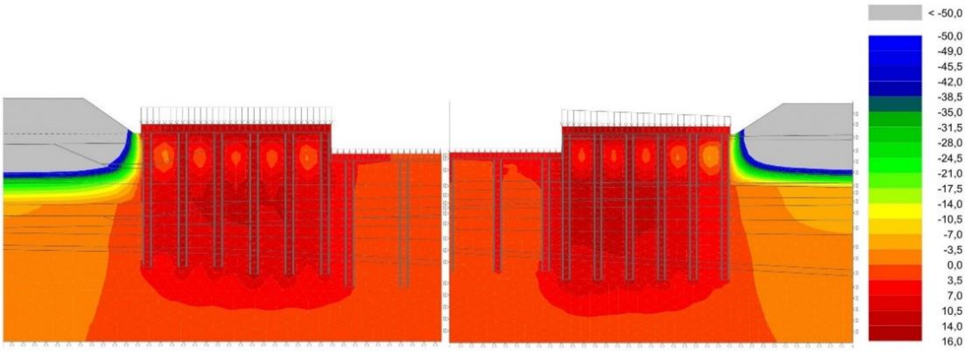

Fig. 5. Settlement in the “pile variant”: B1+1/2G (on the left) and B2+1/2G (on the right)

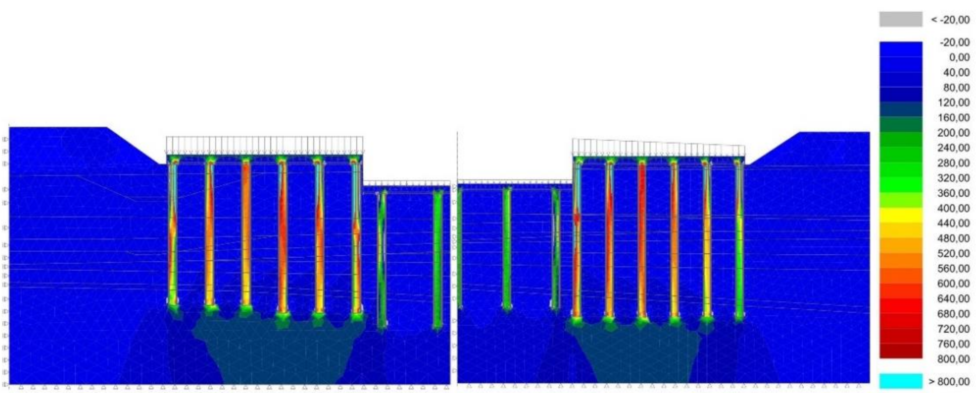

Fig. 6. Additional stresses in the “pile variant”: B1+1/2G (on the left) and B2+1/2G (on the right)

6. Reinforcement the subsoil with concrete columns

In the second variant of the analysis, reinforcement of the subsoil with concrete columns was considered. The calculations were performed in stages: for individual columns and the entire foundation. A single column was modelled using an equivalent axisymmetric model with a volume equivalent to the actual spacing of the columns. Eight models of individual columns were created (Fig. 7), as well as two models in a flat deformation state (Fig. 8, Fig. 9). For building B1, models were created based on the results of CPTU-3 and CPTU-4; for building B2, the tests CPTU-2A, CPTU-7, and CPTU-8 were used, and for the garage, the results of CPTU-3, CPTU-7, and CPTU-8 were utilised. Table 4 presents the settlement values for the respective calculation models, and Table 5 presents the pile load capacities according to the LCPC method. Cooperation between the shafts of the columns and the subsoil was assumed using contact elements with parameters estimated based on the settlement curve obtained from the pile load analysis using the LCPC method. Similar to the pile analyses, six calculation phases were assumed.

The load-bearing capacity of individual columns was additionally calculated using the LCPC method directly from the results of CPTU static soundings, similar to the case of pile foundations.

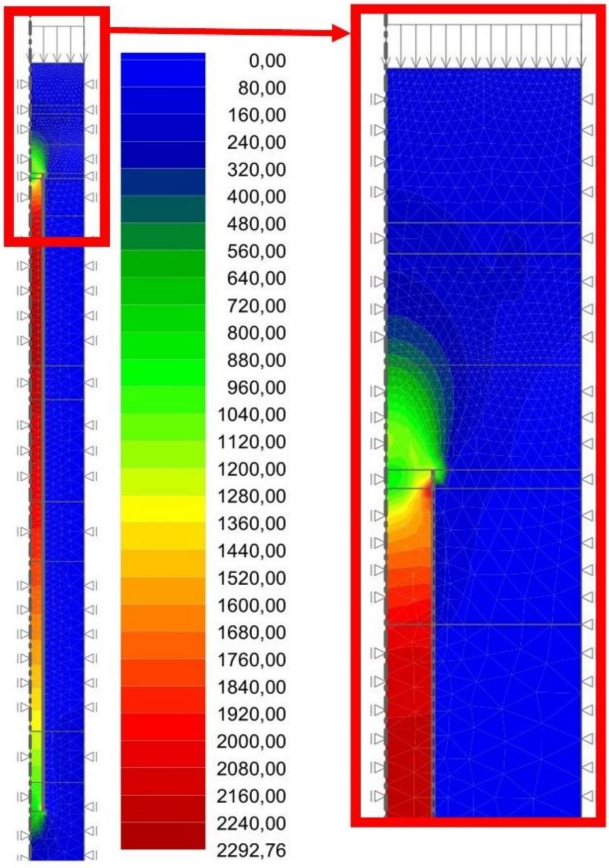

Fig. 7. Stresses in the column under building B2

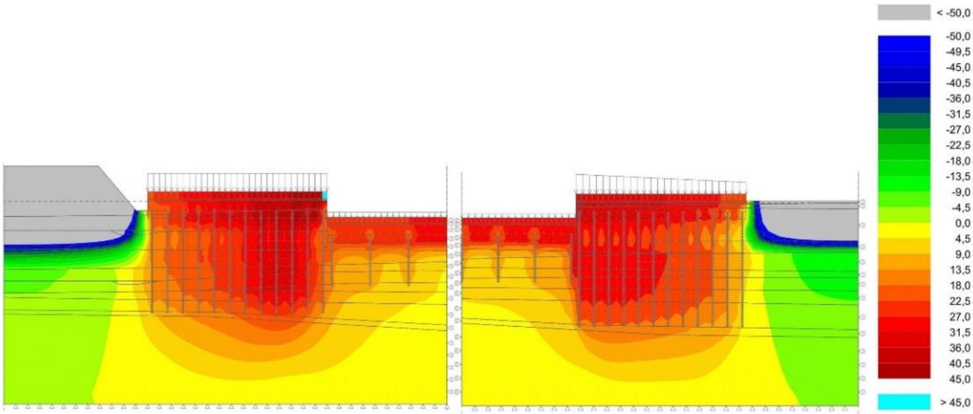

Fig. 8. Settlement in the "subsoil reinforcement" variant: B1+1/2G (on the left) and B2+1/2G (on the right)

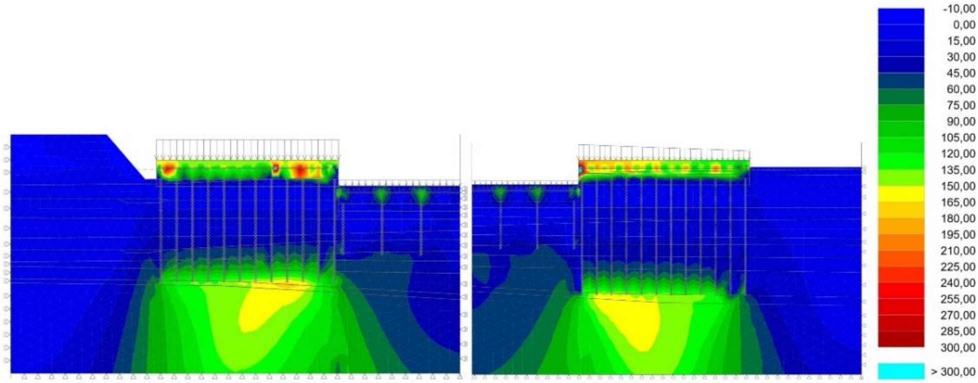

Fig. 9. Additional stresses in the "subsoil reinforcement" variant: B1+1/2G (on the left) and B2+1/2G (on the right)

Table 4. Settlement of concrete columns calculated in axisymmetric models

		B1		G			B2		
		CPT 3	CPT4	CPT 3	CPT 7	CPT 8	CPT 2A	CPT 7	CPT 8
		L=6.0 m	L=8.5 m	L=2.5 m	L=2.5 m	L=3.5 m	L=7.5 m	L=8.5 m	L=7.0 m
Spacing [m]		1,08x 1,08	1.08x 1.08	2.67x 2.49	2.67x 2.49	2.67x 2.49	1.08x 1.12	1.08x 1.12	1.08x 1.12
Plate level	Phase 5	27.5	-189.9	-13.3	-9.3	-10.2	-129.7	-44.9	-59.0
	Phase 4	-12.7	-226.9	-17.6	-19.3	-18.9	-167.3	-81.9	-96.5
		40.2	37	4.3	10.0	8.7	37.6	37	37.5
Column level	Phase 5	23.2	-207.9	-12.7	-11.1	-18.2	-148.4	-60.6	-80.2
	Phase 3	-22.7	-236.5	-17.5	-35.4	-31.6	-177.3	-91.3	-106.6
		45.9	28.6	14.8	24.3	13.4	28.9	30.7	26.4
Subsoil level	Phase 5	26.6	-189.5	-11.7	-9.7	-10.6	-129.1	-44.6	-58.2
	Phase 3	-22.7	-236.5	-27.5	-35.4	-31.7	-177.3	-91.3	-106.6
		49.3	47	15.8	25.7	21.1	48.2	46.7	48.4

Table 5. Analysis of column bearing capacity according to the LCPC method

Case		Maximum stress in column	Maximum load in column	Load capacity (LCPC)	Length	Spacing	Model dimension AS FEM	Load capacity utilization
		[kPa]	[kN]	[kN]	[m]	[m]	[m]	[%]
B1	3	1461.4	103.3	282.5	6.0	1.08x1.08	0.61	37
	4	2743.3	193.8	217.9	8.5	1.08x1.08	0.61	89
G	3	505.9	35.7	141.5	2.5	2.67x2.49	1.46	25
	7	501.1	35.4	58.2	2.5	2.67x2.49	1.46	61
	8	1042.8	73.7	89.6	3.5	2.67x2.49	1.46	82
B2	2A	2730.5	192.9	215.7	7.5	1.08x1.12	0.62	89
	7	2696.3	190.5	254.3	8.5	1.08x1.12	0.62	75
	8	2696.3	190.5	214.2	7.0	1.08x1.12	0.62	89

Ultimately, columns were designed with spacings of 1.08 x 1.08 m and lengths of 6.0 m and 8.5 m for building B1, 1.08 x 1.12 m with lengths of 7.0 m, 7.5 m, and 8.5 m for building B2, and 2.67 x 2.49 m with lengths of 2.5-3.5 m for the garage. The maximum stresses in the columns were 3.5 MPa, providing a significant safety margin compared to the calculated compressive strength of 8.9 MPa for the assumed C16/20 class concrete used for the columns.

7. Conclusions

The aim of the study was to analyse the foundation of a multi-family building consisting of two residential parts connected by an underground garage. Two foundation variants were considered: using foundation piles and soil improvement with concrete columns. In both variants, a foundation slab with a thickness of 50 cm under the buildings and 40 cm under the garage was applied. A total of 1,096 concrete columns with a diameter of 300 mm and a combined length of 7,485.5 m were designed, requiring 528.9 m³ of concrete. Additionally, 334 driven piles with a diameter of 500 mm and a combined length of 3,305.5 m were designed, requiring a volume of 648.7 m³ of concrete. The difference in concrete volume is approximately 120 m³ in favour of the columns, which constitutes nearly 20% of the total concrete volume. For all piles, hoop reinforcement with longitudinal bars #22, #25, #32, and spiral reinforcement with #8 bars was assumed, requiring approximately 99.2 tons of steel. For soil improvement, reinforcement was only applied in columns where bending moments occurred, resulting in reinforcement for 293 columns, or about 27% of the total. The reinforcement consisted of HEA120 I-beams with a combined length of 2,377.5 m and a weight of approximately 47.3 tons.

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