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EXPERIENCE IN DESIGN OF A HIGH-RISE BUILDING WITH A PILE FOUNDATION CONSISTING OF PILES OF DIFFERENT LENGTHS

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ABSTRACT

The article presents the experience of the foundation designing for a high-rise building. After the construction of the underground part of the building, the project was halted for several years. When construction resumed, the height was increased, and it was decided to utilize the existing 28.5-meter-long piles by supplementing the pile field with longer ones. The article highlights the key aspects of the entire foundation design and calculation process, during which several foundation options have been reviewed. Also, the article presents the results of pile testing, including their modeling and validating this model. Based on it, the model of single pile has been validated and the equivalent pile model has been verified. After this, prediction of settlements has been given.

Keywords: piles, pile foundation, piles of different lengths, mutual interaction of piles.

INTRODUCTION

The suspension of construction projects, particularly high-rise buildings, occurs frequently. Upon resumption, a critical challenge arises when the existing unfinished structures become "initial data" for designers, significantly influencing foundation design decisions. Main factors are the state of the soil foundation, changed architectural concepts leading to increased loads, and confined construction conditions due to dense urban development, among others.

As exemplified in the case study discussed in this article, construction of a partially erected building was halted in 2017. Upon resumption, a new architectural concept was adopted, increasing the building's height and resulting in a 15% rise in foundation loads.

The constructed residential building of the tower type has 77 floors, including 2 underground ones with dimensions of the underground part approximately 34 x 56 m with the height of the building 273 m. The adopted structural scheme is a frame-shaft system. This system comprises two primary load-bearing components: a central concrete barrel, which serves as the main element providing spatial rigidity to the entire structure, and a monolithic concrete framework incorporating vertical diaphragms of stiffness for lateral load resistance.

The main difficulty was the existence of a 4-storey part of the high-rise built on pile foundations, consisting of 239 drilling piles, 28,5 m long with a 1 diameter, placed at average spacing of 2,2 m. It was decided to demolish the underground part of the built, and evaluate the possibility to use existing piles for the foundation of the planned building.

Because the loads on the base increased significantly, the load capacity and stiffness of the existing columns was not enough and it was necessary to implement measures to increase the load capacity of the base. The existing piles did not meet the requirements of ULS and SLS.

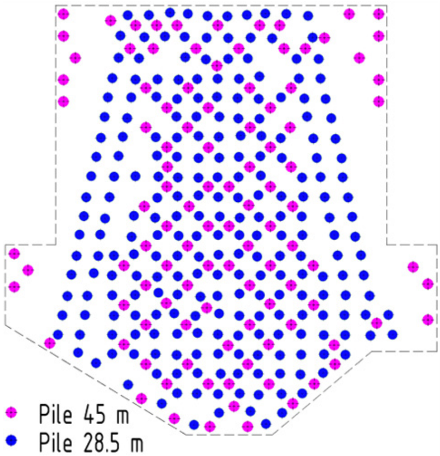

Figure 1 *Pile layout diagram*

Multiple solutions were evaluated during the design phase, such as supplemental piles of the

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same length but larger diameter placed outside the existing pile field, jet grouting and others. In the first version, piles of a larger diameter when positioned on the perimeter created greater rigidity, but increased the grillage deflection. The second option involved complex construction and quality control challenges due to the deep jet grouting. Therefore, the final design adopted additional extended-length piles installed at specific locations along the external contour and beneath the building's stiffening core, positioned between existing pile rows (Figure 1). This layout optimizes structural performance by aligning stiffness distribution with load distribution.

The piles pass through a thickness of sand (18 m) of different size, average density and density. The bottom ends of the 28.5 m long pile are submerged in layer 7 (J3v) and the bottom ends of the piles 45 m long are submerged in layer 8 (J3ox). The subsoils below are clays very stiff and limestones medium-strength, very blocky. The top of the pile is joined by a 2.35 m thick concrete slab (Figure 2).

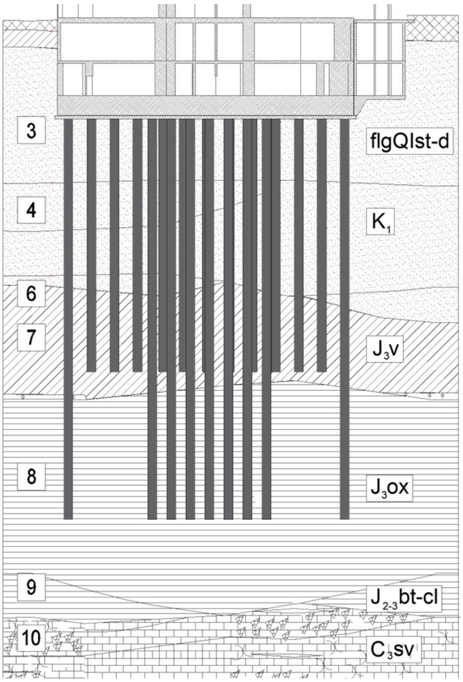

Figure 2 *Subsoil conditions*

VALIDATION OF A SINGLE PILE MODEL BASED ON PILE LOAD TEST RESULTS

At the design stage, the piles were calculated according to the calculation methods of the Code of Rules "SP 24.13330.2021", which subsequently showed a significant underestimation in their stiffness.

Subsequently, a series of single pile settlement calculations with different mechanical parameters of the soils was performed on the basis of the static pile tests. According to the results of the geotechnical investigations (Table 1) the calculation of pile settlement, showed a significant excess of the stiffness of the pile obtained in the pile test throughout all load range. Therefore, the mechanical characteristics given in the results of geotechnical investigations from laboratory and field tests analyzed to identify the reasons for this difference. These mechanical characteristics were then corrected by back analysis method. Due to the importance of taking into account the pre-failure soil deformation and the relatively small area involved in the interaction of the soil, typical for long piles, the HSsmall model was chosen.

During the first validation phase, the following parameters were introduced into the model: overconsolidation ratio for clays and soil deformation characteristics in the area of small shear strains (for calculation according to the Hardening Soil with small strain stiffness (HSsmall) model), whose parameters were adopted taking into account works by Hardin, B.O. (1969) and Vucetic, M. (1991).

Table 1 *Soil properties*

Genesis	Description	E [MPa]	φ [°]	c [kPa]
flgQIst-d K1 (3-6)	Sands medium-dense to dense	26-54	33 - 41	2-4
J_3v (7)	Lean clays stiff	38	23	52
J_3ox (8)	Clays very stiff	37	21	65
$J_{2\text{-}3}bt\text{-}cl$ (9)	Clays very stiff	48	22	79
C_3sv (10)	Limestones medium-strength, very blocky	896	-	-

In the second step, since the graph still showed a significant shortage of stiffness of the pile on the whole loading section, the deformation parameters (E50, Eoed, Eur) were adjusted.

Table 2 *Soil properties after validation based on static load test data*

Genesis	flgQIst-d (3)	K_1 (4)	J_3v (7)	J_3ox (8)	$J_{2\text{-}3}bt\text{-}cl$ (9)
p_{ref}	93	153	540	734	779
E^{ref}_{50}	18	19	27	33	35
E^{ref}_{ur}	57	61	149	113	75
OCR	-	-	2.5	2.0	1.5
$G^{ref}0$	105	153	213	121	175
$\gamma_{0.7}$	1.81E-04	2.33E-04	1.65E-04	4.43E-04	4.12E-04

The soil deformation characteristics affect on the general slope of the graph, namely at small shear deformations the most influence is exerted by E_{ur}, G0 and $\gamma_{0.7}$, at sufficiently large shear deformations the most influence on the graph's slope is exerted by E_{50}. The position of the overbending point is influenced by the strength characteristics and OCR. Because the results of the OCR account are satisfactory, the strength characteristics have been taken without changes.

The results of the two-stage validation show a significant approximation of the graph to the results of the field tests on piles (Figure 3). The soil parameters obtained from the validation will be used in further calculations (Table 2).

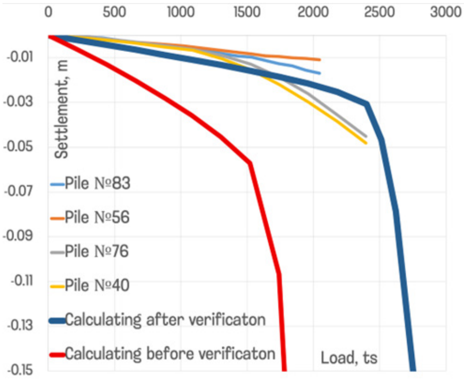

Figure 3 *Results of single pile model calculations before and after validation based on static load test data*

VALIDATION OF THE FOUNDATION MODEL BASED ON AVAILABLE MONITORING DATA AND SETTLEMENT PREDICTION

The ultimate goal of the calculations was to predict the building's settlement for its total lifetime. In the process of carrying out this predict, it was necessary to carry out a calculation taking into account the consolidation and, accordingly, the adjustment of parameters for it. The second goal was to perform these calculations with little labor, time and computational power.

In this moment observations data of settlements have been available for the first year of construction. In April 2025, the building was constructed on 28 floors out of 75, which is equivalent to 40% of the total load.

For the preliminary calculation of the average settlement, taking into account the calculation purposes given above, an equivalent pile model was adopted, which is a cylinder equivalent to the simulated pile group by dimensions within an elastic half-space or layer of final thickness (Figure 4). The equivalent pile diameter (d_{eq}) is a key parameter used to represent the pile group as a single entity in simplified analyses. It is determined from the formula deq = $2\sqrt{A_g/\varpi}$, where A_g is the gross area encompassed by the perimeter of the pile group. According to Aleksandrovich V. F. (2005), Bokov I. A. (2021), Poulos H.G. (1980) and Tomlinson M. (2015) this model shows a good convergence of the average settlement.

Verification of the equivalent pile model was carried out by comparison of a three-dimensional model (Figure 4) for convergence of the average settlement.

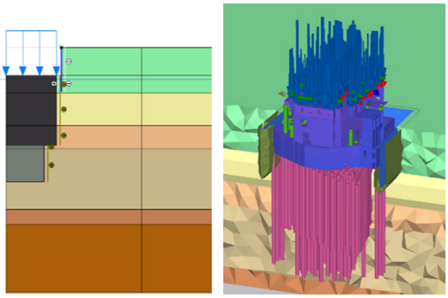

Figure 4 *General view of the equivalent pile and three-dimensional model*

The three-dimensional geotechnical model used as a reference for the calculation of settlement, takes into account the influence of the temporary excavation support, the stages of the pit excavation and the gradual application of the load from the construction of the building structures. The model specifies the necessary part of the building structures (7 floors) to take into account the interaction between the system, the foundation and the soil base. This approach provided high accuracy, but at the same time led to a fine finite-element mesh and therefore long calculation time.

The initial stiffness of the equivalent pile was taken from the formula given by Aleksandrovich V. F. (2005):

$$E_z = \frac{E_p F_p + E_1 (A - F_p)}{A} \tag{1}$$

where E_p is the Young's modulus of the pile material; F_p is the cross-sectional area of the pile; E_1 is the deformation modulus of the top layer of the soil; A is the pile cell area. The unit cell area associated with each pile in a square grid is A=s², where s denotes the pile spacing. Due to the fact that the foundation consists of a piles of different lengths, the equivalent pile model is adopted with 2 different deformation modulus of the equivalent pile body, the boundary of which passes at the level of the shorter pile ends. According to the HSsmall model the deformation properties of soils were taken from the validation results of the calculation of a single pile.

During the first validation phase, the parameters of the body rigidity of the equivalent pile and the parameter of the interface element along its side surface were selected for the average settlement. Comparisons were made by the average head-pile settlement to the average grillage settlement in the three-dimensional model and by the average settlement end of the equivalent pile to average settlement by the settlements diagram of the soil mass at the level of the piles ends in the three-dimensional model. The bottom surface settlement was mainly regulated by the characteristics of the interface element, the top surface settlement more depended on the rigidity of the body of the equivalent pile.

Figure 5, based on the results, shows a comparison of settlement diagrams along both the top surface and the pile's end surface of the equivalent pile, presenting for each surface the results from the three-dimensional model (upper diagram) alongside those from the equivalent pile model (lower diagram). The discrepancies in the diagrams of settlements can be explained by the fact that in the equivalent pile model the shear rigidity of the pile body is higher than that of the "grillage-piles-interpile soil" system - for calculating the average settlement we can neglect this and accept the model verification results for subsequent calculations. Thus, the model of an equivalent pile demonstrates good convergence. This finding aligns with the work of Bokov I. A. (2021), where the author examined the limits of applicability of the equivalent pile model and found convergence at pile spacings of 3d and 6d in the absence of a highly rigid underlying layer.

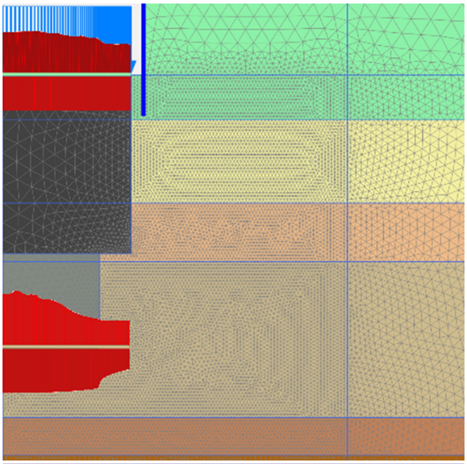

Figure 5 *The result of verification of the equivalent pile model for average settlement in the three-dimensional model*

Figure 6 shows the result of the settlement calculation in comparison with the observation data. The graph shows the settlement values in the drained setting (blue points), which corresponds to the settlement calculation for the final state. Given the significant magnitude of the rheological settlement component, consolidation was explicitly considered in the subsequent calculations.

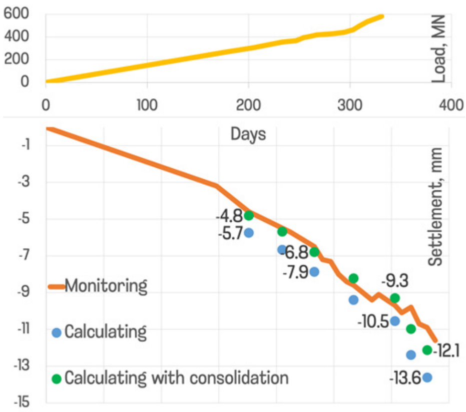

Figure 6 *Comparison of settlements obtained using the model of the equivalent pile with available observation data on building settlements*

Taking into account consolidation, the initial calculation was performed on the parameters given in the geotechnical investigations data. Subsequently, for a more complete or reliable accounting of the factors determining the settlement in time, the parameters regulating the undrained behavior of soils (permeability, Skempton parameter) were adjusted based on the data of Shulyatyev, O. A. (2017) - the result is shown in the table 3 and in the same figure by green points.

Table 3 *Soil properties for calculations taking into account consolidation*

Parameter	J_3v (7)	J_3ox (8)	$J_{2-3}bt$-cl (9)
Permeability - initial (top) and accepted in calculations (bottom), m/day	0.010E-03 0.013E-03	0.009E-03 0.011E-03	0.009E-03 0.011E-03
Skempton parameter - initial (top) and accepted in calculations (bottom)	0.5094 0.6086	0.2547 0.3469	0.5234 0.6861

The obtained convergence of the calculation results taking into account the undrained behavior of clay soils was accepted as sufficient for predicting the settlement of the building.

The forecast for the building settlement showed that the dissipation of excess pore pressure in the foundation will occur over 37 years, and the settlement at the time of completion of construction will be 39 mm (Figure 7). Upon completion of the consolidation process, the predicted settlement will be 50 mm.

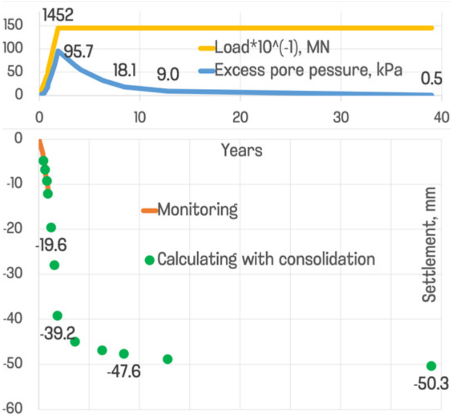

Figure 7 *Prediction of building settlement based on model of the equivalent pile*

CONCLUSIONS

The article demonstrates the importance of static pile testing, especially for high-rise buildings, and the significance of the settlements monitoring of already erected buildings. Based on these data, it is possible to validate models, which allow for more realistic deformation values and more optimal design solutions.

For preliminary calculations of average settlement, in terms of labor costs and time, the optimal solution may be to perform the calculation using the equivalent pile method - this is especially relevant when it is necessary to carry out a large series of calculations to validate the model.

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