Foundation of the Building on Short Concrete Piles in a Thin Layer of Non-Cohesive Soils

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Abstract. The paper presents measurable benefits resulting from optimization of selection, appropriate for local ground-water conditions, type of foundation of a high residential and service building with ten residential floors, two service and two underground ones. The original design solution expected the replacement of up to 8.5 m p.p.t. soft cohesive soils (including organic ones) on gravel mixed with sands. The foundation of the high building is planned as a direct foundation on depth of 6.9 m below ground surface on a foundation slab under a residential part and the service part on a foundation framework on the prepared substitute-subsoil. After a detailed analysis of the data, the contractor reported the possibility of engineering optimization initially the pre-engineering adopted in the project foundation, significantly reducing the investment costs. It was proposed to change the direct foundation on indirect on short foundation piles with a diameter of 600 mm, the base of which is located in the subsoil, shallowly located layer of gravel mixed with coarse sands, about 2.0 m thick. Below the granular soil layer there is at least several dozen meter thick layer of Krakowiec clays. Numerical simulations of the foundation were made, from which it appears that due to the settlement of the building, it is more advantageous to form the piles shallowly in the non-cohesive soils layer rather than deeper. An additional benefit of the adopted solution - foundation of the building on concrete piles - allowed to reduce the trench by 1.5 m and to protect the sheet piles with only one level of struts inside the trench. The settlements values predicted in the numerical model, have been verified by monitoring, which was carried out during construction as well as during the five-year operation of the building. The real settlements of the building reached the level of 45.8% of settlements values of the numerical model, of which 37.5% of real settlements occurred at the stage of completion shell of the building. The discrepancy between the real and model values of settlements may result from the underestimation of the soil medium parameters in the numerical model.

1. Introduction
Projects of foundations of building objects usually take into account the basic requirements concerning limit states of external and internal bearing capacity as well as serviceability limit states for traditionally used methods of foundation in a given region.

Designers' habits, requirements of investors and geotechnical conditions of subsoil have an impact on the solution of foundations in a given region. The economic aspect of building foundations is sometimes overlooked, assessed at the end of the design process or even by the contractor at the beginning of the building of the object. In the case of the foundation of the building, the contractor...
reported the possibility of engineering optimization of the foundation, adopted in the initial project, allowing to restrict the cost of foundation of the building.

2. Engineering optimization of the building foundation
The building was designed as a monolithic reinforced concrete structure and it consists of ten residential storeys, two service floors and two basement storeys of garages. A characteristic cross-section of the building is shown in Figure 1 (Gąska, 2012).

The building is located on the Wisłok river floodplain terrace in Rzeszów. The geotechnical conditions in the place of foundation of the building were determined on the basis of geotechnical documentation made by the Geotech - Department of Geological Services and and Design Construction of Building and Environmental Protection in Rzeszów, in which two basic soil complexes were found:

- Pleistocene-Holocene complex of river-terrace sediments, deposition to a depth of 10.5 m below the ground level (Layers I and II in Figure 1 (Gąska, 2012),
- Miocene complex of marine sediments, a few hundred meters thick, located directly below the river-terrace sediments (Layer III in Figure 1 (Gąska, 2012).

The complex of river-terrace sediments was divided into two layers:

- layer of river-terraces alluvial soils (fluvsole) in the form of loamy and silty warps with lenses of sandy warps, tangled with organic warps and even peat. The thickness of the alluvial soils is 8.5 m (Layer I in Figure 1 (Gąska, 2012),
- layer of coarse sands plus gravel about thickness 2.0 m (Layer II in Figure 1) (Gąska, 2012).

It should be noted that Subcarpathian organic soils represented in this case by various warps and peats are characterized by an extremely diverse structure, properties and geotechnical parameters (Straż, 2011). The sea sediment complex is built from Krakowiec clays. In the layer of coarse sands with gravel there is underground water with a tilted groundwater table - the apparent (piezometric) groundwater table stabilizes at the level of 3.1 m below the ground level and can be changed in the range of ± 2.0 m (Gąska, 2012).

The level of direct foundation (reinforced concrete foundation slab up to 1.0 m below the residential part and reinforced concrete foundation framework co-operating with a 0.3 m thick reinforced concrete slab under the service part) is located 6.9 m deep below the ground level, i.e. in the river-terraces alluvial soils. Below the building foundation level (up to the ceiling of coarse sands with gravel), it remains about 1.6 m alluvial soils (Gąska, 2012). In the original design solution, it was predicted to make a replacement of alluvial soils under the foundation of the building for mixed gravel and sand. For this purpose, it was necessary to make a trench with a minimum depth of 8.5 m, which was secured with a sheet pile wall of heavy steel sheet piles, strutting in two levels.

In order to reduce the costs of realization (the issue discussed by Wang & Kulhawy (2008), Paul, Chow & Kjekstad (2002) and Henderson & Pickles (2004)) and secure the trench, it was proposed to make a foundation of the building on short concrete piles, passing through soft cohesive soils in thickness of 1.6 m to a thin layer of non-cohesive soils (2.0 m in thickness). The foundation of the building on concrete piles allowed to reduce the trench by 1.5 m and to protect the sheet piles with only one level of struts inside the trench. Density and location of piles under the building was adopted on the basis of calculations of their bearing capacity according to PN-B-02482 (1983) and impacts from the building. Under the building were designed 355 piles, made with a continuous drill bit from the ground level with a diameter of 600 mm (before making the trench). The scheme of the foundation, in a characteristic cross-section, is presented in Figure 2 (Gąska, 2012).
Figure 1. A characteristic cross-section of the building (developed on the basis of a section from the working project of a residential building with a service part and an underground garage: I - river-terraces alluvial soils, II - coarse sands with gravel, Krakowiec clays).

Figure 2. Scheme of foundation of the building on concrete piles (is based on the basis of a cross-section of the working project of a residential building with a service part and an underground garage.)
3. **Numerical analysis of the foundation of the building on concrete columns**

The minimum thickness of non-cohesive soils in accordance with the requirements adequate of PN-B-02482 (1983) for foundation of the building on concrete piles with a diameter of 600 mm is 3.5 m - in the case of this analysis, the requirement is not fulfilled, because the thickness of non-cohesive layer is 2.0 m.

Due to the atypical foundation of piles in a thin layer of foundation, numerical simulations were performed using the finite element method in the Plaxis B.V., Delf, Holland program, in which two numerical models were built:

- model I, in which concrete piles are sinking in a non-cohesive ground to a depth of 0.5 m (1.5 m of a non-cohesive soil layer stays under the bases of columns) according to Figure 3 (Gąska, 2012),
- model II, in which concrete piles are sinking in a non-cohesive ground to a depth of 1.2 m i.e. a depth equal to twice the diameter of columns (there is a 0.8 m non-cohesive soil layer under the bases of columns) according to Figure 4 (Gąska, 2012).

The models used a constitutive soil center according to Coulomb-Mohr and in the case of concrete structures, linearly-elastic. Material parameters of the models are summarized in Table 1 (Gąska, 2012).

| Material                  | Unit Weight | Angle of internal friction | Cohesion [kPa] | Eodometric modulus of primary compressibility [kPa] | Modulus of elasticity [kPa] | Poisson's ratio [-] |
|---------------------------|-------------|----------------------------|----------------|----------------------------------------------------|-----------------------------|---------------------|
| Alluvial soils            | 18.0        | 7.0                        | 5.0            | 5000                                               | 3000                        | 0.35                |
| Coarse sands with gravel  | 19.0        | 32.0                       | 0.0            | 7500                                               | 5500                        | 0.30                |
| Concrete                  | 24.0        | -                          | -              | -                                                  | 300000000                   | 0.20                |

The basement storeys have been introduced into the models as a concrete block (they constitute, along with the higher storeys, a spatial reinforced concrete box without dilatation). The concrete block was loaded with a substitute uniformly distributed impacts - respectively for the residential-service-garage part as well as the service-garage part. The vertical displacement of the foundation, which can be verified and monitored in the construction and operation conditions of the building, was adopted as the decisive parameter of the model. The vertical displacements of the building obtained as a result of numerical analyzes are summarized in Table 2 (Gąska, 2012).

| Model | Vertical displacement value |
|-------|-----------------------------|
|       | $V_{\text{max}}$ [m] | $V_{\text{min}}$ [m] |
| I     | 0.024                       | 0.004                |
| II    | 0.030                       | 0.002                |
In the case of a shallow penetration of piles in the non-cohesive soil layer (model I), the piling up of the soil towards the higher, weak, alluvial soils (mad) layer can be observed (ultimate limit state analogous to the direct foundation - in this case a pile). This is accompanied by large vertical displacements of the foundation, whose values from 2.4 to 0.4 cm are acceptable and not dangerous for the overall stability of the building. In the case of deep depression of piles in the non-cohesive soil layer (model II), a state similar to the breaking of piles is observed through a non-cohesive soil under the foundations of piles to the below-lying layer of clay.

Figure 3. Vertical displacements for model I (vertical scale = horizontal scale, expressed in meters).

The biggest effort of the clay layer is accompanied by vertical displacement of the foundation, whose values from 3.0 to 0.2 cm are acceptable and safe for the stability of the building. From the vertical displacements of the building foundation, obtained in the model I, results that the lower building tilts towards the high part (the bank angle is 0.033 degrees) than in the case of the II model (the bank angle is 0.046 degrees) is visible. As a result of numerical analyzes of the foundation of the building, the foundation according to model I was chosen for implementation.

Figure 4. Vertical displacements for model II (vertical scale = horizontal scale, expressed in meters).
4. Real values of vertical displacements of the building
During the construction, geodetic measurements of vertical movements of the building were carried out in four points (bench-marks) installed on the corners of the building. The average values of vertical displacements of the building in a characteristic cross-section according to Figure 1, after being made from the lowest to the highest storey of the building, are presented in Table 3. Vertical displacements of the extreme points in a characteristic cross-section (according to Figure 1), measured geodetically at the stage of completion construction of shell of the building are from 0.1 to 0.9 cm. They represent 25.0 and 37.5% respectively of the displacement values obtained in the numerical model. This condition may result from the real effect of strengthening the soft layer of alluvial soils (mad) with concrete piles. The reinforcement results in much better properties of the soil-pile composite (Godlewski, 2007), which effect was not taken into account at the numerical modelling stage.

Table 3. Average values of vertical displacements of the building at the construction stage in a characteristic cross-section according to Figure 1.

| Number of residential floors | The average value of vertical displacement at the extreme point of the residential-service-garage part [m] | The average value of vertical displacement at the extreme point of the service-garage part [m] |
|-----------------------------|-------------------------------------------------|--------------------------------------------------|
|                             | $v_{C1i}$ [m]                                   | $v_{C2i}$ [m]                                    |
| 1                           | 0.000                                           | 0.000                                            |
| 2                           | 0.000                                           | 0.001                                            |
| 3                           | 0.001                                           | 0.001                                            |
| 4                           | 0.002                                           | 0.000                                            |
| 5                           | 0.002                                           | 0.001                                            |
| 6                           | 0.003                                           | 0.001                                            |
| 7                           | 0.007                                           | 0.000                                            |
| 8                           | 0.007                                           | 0.000                                            |
| 9                           | 0.009                                           | 0.000                                            |
| 10                          | 0.009                                           | 0.001                                            |

After completion of the construction of shell of the building, geodetic measuring points (bench-marks) were installed on the facade of the building. The research on vertical displacements of the building was continued for six consecutive years and the average displacement figures are presented in Table 4. Vertical displacement of the extreme points of the characteristic cross-section of the building during the three-year exploitation reached extreme increments of 0.2 cm. In the later period, the process of stopping the growth of vertical displacements of the building is observed.

5. Conclusions
Due to the small thickness of the foundation layer, numerical simulations of two cases of foundation of piles were made: the first simulation (model I) concerned a shallow location of the base of piles in the foundation layer; the second simulation (model II) concerned the deep location of the base of piles in the foundation layer. Based on the analysis of numerical models, it was decided to use a shallow foundation of piles in a thin layer of non-cohesive soil, resulting in the smallest settlements of the building.
Table 4. Average values of vertical displacements of the building at the building operation stage in a characteristic cross-section according to Figure 1 (Gąska, 2012).

| Date of measurement | The average value of vertical displacement at the extreme point of the residential-service-garage part [m] | The average value of vertical displacement at the extreme point of the service-garage part [m] |
|---------------------|-------------------------------------------------|-------------------------------------------------|
| April 2009          | 0.000                                           | 0.000                                           |
| April 2010          | 0.002                                           | 0.002                                           |
| April 2011          | 0.002                                           | 0.001                                           |
| April 2013          | 0.001                                           | 0.001                                           |
| April 2015          | 0.001                                           | 0.001                                           |

In order to control the real settlements of the building, geodetic monitoring was introduced, which due to technological reasons was divided into the construction phase and the stage of building exploitation. The measurements of the real settlements of the building indicate the compatibility of the settlement form of the building with the form of settlements, obtained as a result of numerical modeling. After completion of the construction and five-year operation, the real settlements of the building reached the level of 45.8% of settlements values of the numerical model, of which 37.5% of real settlements occurred at the stage of completion shell of the building. The discrepancy between the actual values of building settlements and model settlements may result from the effect of reinforcing the soft soil layer with concrete piles, which was not included in the numerical model or underestimation of the soil medium parameters in the numerical model.

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