Geotechnical monitoring results of 22-storey buildings on combined strip pile foundations with prestressed soil bases

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Abstract. The article describes the concept of combined strip pile foundations with prestressed soil bases by pressing them with the cement mortar. The soil base pressing makes it possible to regulate and control the soil stress-strain state by creating prestresses that allow increasing the rigidity of the soil base and reduce the level of the base settlement and deformations of the above-ground part, the values of which determine the operational suitability of structures and their technical and economic indicators. The authors present the results of the applied combined strip pile foundation implementation in Tyumen (Russia) during the construction of two 22-storey high monolithic-frame apartment buildings as an alternative to pile-raft foundations based on composite driven piles, which helps to reduce the estimated cost and timing of the foundation constructions. Also the article describes the construction operations and contains the geotechnical monitoring results, which confirmed the operational reliability of the implemented solutions.

1. Introduction

By now, 90\% of the natural resources of Russia is concentrated in remote severe climatic parts of Siberia and the Far East. For instance, Western Siberia is considered to be the heart of Russia’s energy sources, since up to 40\% of the gross revenue of the country is provided with the oil and gas producing industry in Tyumen region only. According to the long term forecast, there is a positive dynamics of development of these regions for the coming 50-100 year period.

Together with exploitation of resources, the development of urban, industrial and transport infrastructures is being planned. The urban infrastructure includes constructions of multistoried (up to 25 storey) buildings, different large administrative, sport and social institutions, sometimes in adverse engineering, geological and hydrogeological conditions. The industrial field is being highly developed due to oil and gas processing plants and infrastructure on the territory of the regions. The above mentioned facilities are characterized with high levels of foundation loads, their locations away from building sites, from reliable and massive transport corridors. The indicated peculiarities make the building process more complicated, risky, reduce safety and lead to cost increases. Thus, the existing state of the building industry is characterized with fast construction operations as well as high level of risks and extremely high levels of resource- and energy consumptions. These are largely caused by lack of professional designers in the field of geotechnical engineering and result in an increasing number of failures of some elements and building projects. Foundation engineering is one of the little studied and most complicated fields of constructions, though it can significantly reduce resource-and energy consumption of the buildings process. In fact, the consumption of reinforced concrete for foundations reaches in average 10-15\% of the whole amount of reinforced concrete for one building in...
residential, industrial, agricultural, energy and transport constructions. In such constructions as chimneys, power transmission towers, and on poorly surfaced soil foundations characteristic for advanced and developing areas of Russia, the consumption of reinforced concrete is about a half of the total amount of costs. It should be taken into consideration that more than 40% of all accidents and failures of constructions are connected with bottom and foundation problems. It is necessary to work out and used advanced systems of foundations, efficient foundation constructions and methods of their calculation. These issues are often discussed at different Russian and international scientific conferences [1]. Nowadays, systems with regulated properties tend to be widely used. In that case engineers, designers, scientists play an active role in optimizing the strain stress states of the system foundation-basement soil and making an efficient interaction of different elements of the given system. For example, if we change properties of basement soils by transforming them with various methods, using new types of foundations, considering constructive and static works of superstructures with the help of advanced computing instruments, we can regulate the interaction of geotechnical constructions with basement soils and significantly reduce construction risks, thus improve safety and economic factors.

The use of weak highly compressible soils as bases for various buildings and structures can be achieved by regulating and controlling the stress-strain state of the soil base as part of the base-foundation-above-ground system. It is effective to regulate and control the stress-strain state of the soil base by creating pre-stresses in a three-phase environment that allows increasing the rigidity of the soil base and reducing the level of base settlements and deformations of the above-ground part, the values of which determine the operational suitability of structures and their technical and economic indicators [2].

Combined strip pile foundations (CSPF) with a possible pre-stressing of their soil bed by its pressing with the cement mortar (figure 1) are considered to be such types of foundations for high and high-rise residential building [3].

Piles of the combined foundation eliminate the lack of soil bed stiffness and are not located under the entire area of the building with certain spacing in two directions, but directly under the force lines of loading (load-bearing walls, columns). The slab of variable stiffness, which unites strip pile foundations, is less resource-demanding, and location of the entire working reinforcement through the main tensile stresses makes it possible to take the bending moments and shear forces effectively after the external (operational) loads are applied to the foundation.

The efficiency of CSPF with pressing the soil base is as follows:

- The structural properties of the soil stressed with pressing can be significantly improved in the foundation, and the soil compressibility is reduced in the active layer.
- The soil bed stressed with pressing allows an additional pressing to be created by the lateral pressure of the upper part of piles resulting in their load-bearing capacity increase.

![Figure 1. CSPF prior to and after pressing](image-url)
• During the first and (possible) subsequent cycles of loading and unloading with pressing, the soil accumulates residual deformations and residual stresses (lateral pressure) affecting the stress-strain state of the soil bed directly under static loading of the foundation. In the initial stages of the operation load, the soil behaves in accordance with the secondary loading module in the active layer [3].

• There come decreases of materials by reducing the consumption of concrete and steel.

Moreover, it guarantees elimination of de-structuring arising due to weather, groundwater and hydrodynamic pressure impacts on the soil bed, dynamic impacts of mechanisms and errors of builders during ground operations.

2. Materials and Methods

2.1 Combined strip pile foundations with the prestressed soil base

Experimental and numerous theoretical studies have successfully applied combined strip pile foundations with pressing the bed in Tyumen during the construction of two 22-storey high monolithic-frame apartment buildings (GP-1.1, GP-1.2), as an alternative to pile-raft foundations based on composite driven piles, which reduced the estimated cost and timing of the foundation construction.

The depth of the foundation is 2.4 m from the daylight surface.

According to the results of engineering and geological investigations, on the construction site from the surface to a depth of 1.5 m, there are bulk soils, below there are tight plastic clays with loam interlayers (E = 9.48 MPa) 1.0-1.7 m thick, soft plastic loam (E=8.48 MPa) 4.5-14.3 m thick, rigid loam with interlayers of sand (E=11.7 MPa) 1.5-8.6 m thick, fine sand of medium density (E=12.56 MPa).

The general designer has proposed the following foundation options with a 1.0 m thick cap plate. The first variant is the combined piled-raft foundation based on 400 driven reinforced concrete piles 12 m long; the average design settlement of this foundation was $s_u=20.1$sm, which exceeded the standard limit values and required the use of composite or bored piles. This resulted in a second option, based on 320 composite cast-in-place reinforced concrete piles with a total length of 16 m, which the client did not agree with.

The authors proposed and developed the combined strip pile foundations with pressing the soil base and subsequently carried out scientific and technical construction supports including geotechnical monitoring. The overall dimensions of the foundation in the axes are 26.0m x 25.7m. The 1.0m x 1.0m cross-section rigid pile cap is located under the load-bearing walls and columns. The foundation piles are rigidly connected to 10 and 12 m long reinforced concrete piles, with a total of 220 piles, staggered at 3d spacing. In the spanning section, the shell section, represented by hollow cylindrical reinforced concrete shells with a thickness of t=150 mm and single-layer reinforcement, is built on an artificial macadam base (figure 2). The inclusion of the combined strip pile foundations in conjunction with the basement walls and its slab created a rigid box structure, which allowed internal forces to be redistributed and equalized the deformation of the whole structure [4].
Figure 2. Combined view of piles layout (left) and foundation (right).

This variant allowed the average design settlement to be reached $s_n=14.5\text{sm}$. The estimated cost of the combined strip pile foundations of the two buildings with pressing the soil base compared to the proposed 320-component 16-metre pile of the combined piled-raft foundation variant decreased from 33.5 to 18.6 million rubles (figure 3). Overall efforts have decreased from 11,800 to 6,800 man-hours. This economic effect was achieved by applying the combined strip pile foundations:

- by eliminating composite piles and decreasing the total number of piles by 30-35%;
- by a 30-40% decrease in concrete and reinforcing steel consumption;
- by a 35-40% decrease in overall efforts.
2.2 Building process of the foundations soil base pressing

The work of the soil base pressing consists of preparing a mortar of a given composition and consistency and then pumping it into the sub-base (crushed stone bed). In this case the injection must be carried out at a certain pressure, in a certain order over the spans and in a certain period of construction, which are set out in the construction project of the combined strip pile foundation and in the method statement for the regulation of the strain-stress state of the soil base.

The pressure test set-up included equipment preparation (injection units, mixers, pumps, gauges, water containers), storage of mortar mixture components (cement, plasticizer) as well as the processes involved in the injection of the cement slurry [5].

The leading process of soil base pressing was based on the organization of work using an injection unit, which included a mixing station and an injection plunger pump. The team for the work consisted of a mortar pump operator and two workers.

The soil base pressing period was set under the condition that the total load on the foundation did not exceed 30%, which was about 80 kPa. As a result, for GP-1.2, a soil base pressing period was set 0.15p and 0.2p for GP-1.1, which in both cases did not exceed 20% of the total load, where p=275 kPa was the final pressure on the soil (figure 4). Thus, the start of the pressing process on both combined CSPF was carried out during the construction of 5-6 floors of the building frame, with masonry work on the external walls and internal partition walls on the ground floors.
A water-cement slurry with W/C=0.6 was used for the soil base pressing. The main component was Portland cement (M400) with an additional plasticizer \[5\]. The mortar was mixed at the mixing unit, then fed into a storage tank, from where it was pumped to the pumping unit, and through the high-pressure line and injector into the sub-shell space (Figure 5).

The pressing of the soil in accordance with the developed organizational and technological documentation was carried out in the sequence shown in Figure 6. The pressure of the pressing process for the outer and inner bays was assumed to be \(p_{\text{press}} = 0.5 \text{ kgf/cm}^2\) and \(p_{\text{press}} = 1.0 \text{ kgf/cm}^2\) respectively.

The pressure increase in the pressing process makes the shell rise. The pressing pressure was maintained at the set value for 4 hours and was monitored by means of pressure gauges with media separators mounted on the test tubes (figure 7 (b)). The shell uplift was monitored \[6\] by means of a 6PAO deflectometer (figure 7 (a)).
Figure 7. Control and measuring equipment for pressing of the soil base: (a) is 6PAO deflectometer for monitoring of shell uplifts; (b) is the industrial pressure gage; (c) is the injection through the grout pipe.

In this way, the methodology developed for the organization of the soil base pressing and quality control work has made it possible to carry out the adjustment of the strain-stress state of the soil in accordance with the construction project and to ensure the operational reliability of the building.

3. Results and discussions
Scientific and technical support and geotechnical monitoring were carried out to ensure construction safety and the operational reliability of the buildings during the works [7]. The perimeter of the basement was covered by external deformation control benchmarks (figure 8). In the monolithic walls inside the basement, internal benchmarks were made. With a basement height of 2.2 m, the internal benchmarks were 10 cm from the floor, which was caused by the need for a 2.0-metre long levelling rod.

Figure 8. A settlement mark.

All of the settlement marks were of the fixed type and were rigidly fixed to the monolithic parts of the frame. There were 25 elements installed on GP-1.1 and 20 elements installed on GP-1.2.

The constructions have been monitored right from the beginning. The GP-1.2 foundations were concreted in the first half of March and GP-1.1 foundations in the second half of March 2014. Three weeks after each foundation was concreted, the basement walls and slabs were completed, settlement marks were installed and geotechnical monitoring commenced.

Figure 9 shows a picture of the geodetic settlement isolines corresponding to a particular measurement step. For clarity, the settlement isolines were aligned with the basement plan.
In all phases of construction, the maximum deformation is realized in the central area of the foundation, the minimum deformation is realized along the perimeter of the basement (along the outer walls). The redistribution of forces and levelling (flattening) of foundation settlement was achieved by implementing a rigid box basement of the building [8].

The soil base deformation of the foundations of both buildings (figure 10) developed uniformly during the construction. According to the geotechnical monitoring results, the average settlement was 11.6 cm (figure 11), with a maximum relative difference in settlement $\Delta s/L = 0.00075$, which fully meets the requirements of the regulations [9]-[12]. At the time of the facility commissioning of the buildings (spring 2016), the foundation was subjected to a design load corresponding to an average

\[ T = 31 \text{ d}; \quad q \approx 6\% ; \quad p_{avr} \approx 17 \text{ kPa}; \]
\[ s_{avr} = 3.3 \text{ mm} \]

\[ T = 157 \text{ d}; \quad q \approx 46\% ; \quad p_{avr} \approx 130 \text{ kPa}; \]
\[ s_{avr} = 32.9 \text{ mm} \]

\[ T = 304 \text{ d}; \quad q \approx 70\% ; \quad p_{avr} \approx 195 \text{ kPa}; \]
\[ s_{avr} = 65.6 \text{ mm} \]

\[ T = 497 \text{ d}; \quad q \approx 90\% ; \quad p_{avr} \approx 275 \text{ kPa}; \]
\[ s_{avr} = 113 \text{ mm} \]
pressure of 275 kPa. As of 2021, the deformations have stabilized and the foundations are in a workable technical condition.

![Figure 10](image)

**Figure 10.** General view of two 22-storey buildings in Tyumen.

The results of the geotechnical monitoring are shown in figure 11.

![Figure 11](image)

**Figure 11.** The results of the geotechnical monitoring. Quality control of KSPF building processes.

According to the authors’ calculated algorithm, pressing of the soil bed reduced the settlement of the combined strip pile foundation by 20-25%.

4. Conclusion

The soil bed pressing in the early stages of construction can decrease the final settlement values by 20% or more, by significantly expanding the scope of the combined foundations made with standard single-section reinforced-concrete piles for building and structures of 25-35 floors in height. The use
of the combined strip pile foundation with the prestressed soil base by pressing as foundations for two 22-storey residential buildings has decreased the estimated cost of constructing foundations by 30-40% and the labor intensity by 40% compared to the combined pile-raft foundation based on composite driven piles. Safety and maintainability during all phases of the construction were ensured by systematic geodetic measurements, which confirmed the operational reliability of the adopted solutions.

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