Experience of instrumental monitoring of the stress state for the soil base - piled raft foundation system

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Abstract

As part of the scientific and technical support of a construction site [1-5] in the city of Kharkiv (Ukraine), automated instrumental monitoring of the stress state of the combined piled raft foundation of the facility was carried out. The building has 7 floors and a mezzanine floor, including 2 floors of an underground parking, 5 floors of a shopping and entertainment zone. The building has a combined framed and diaphragm structural system. The building system is a cast-in-situ frame with reinforced concrete cast-in-situ girderless floor slabs. The foundation is a combined piled raft foundation with a concentration of bored piles under the load-bearing elements of the frame. For the construction project, during site preparation and civil works, 23 (twenty-three) transducers of two types were installed, including strain meters (Geosense, England) to determine stresses in bored piles and in the upper and lower reinforcement grids of the raft; and pressure cells (Geocon, USA), which were placed under the bottom of the raft. According to architectural and design solutions, an analytical BIM-model of the building was developed in the Revit software, which is conveniently integrated with the SOFISTIK design software package, where the calculations of the building structures in the base - foundation - structure system. The monitoring results showed that the largest relative differences between the actual and rated forces are: 9.9% for moments forces in the raft and 9% for longitudinal forces in piles.

Keywords: Stress Strain State, Combined Piled Raft Foundation, Soil Base

1. General information about the object of monitoring

The object of survey is the NIKOLSKY shopping and entertainment center, located at 2, Pushkinska Street in the city of Kharkiv (Ukraine). The developer is Budhouse Group (Kyiv, Ukraine).

The construction project is a building that has a complex configuration in plan in the numerical axes of 1 to 22 and alphabetical axes of A to П with dimensions in plan 180.6 × 103.2 m. The main load-bearing structures of the object are made of cast in-situ reinforced concrete. The structural system is a skeleton and diaphragm frame with girderless cast in-situ floors. The building has seven floors: two floors of an underground parking and 5 floors of shopping and entertainment area and a mezzanine floor with a partially glass covered dome-shaped roof. The spatial rigidity of the building is ensured by the behavior of horizontal and vertical reinforced concrete load-bearing structures of the building, columns and stiffening diaphragms, cast in-situ floors, cast in-situ stairwells and elevator shafts. The general views of the buildings are given in Figs. 1, 2.

The object uses a combined piled raft foundation with a concentration of bored piles of different diameters (d=1.0 m; d=1.2 m and d=1.5 m) with a length of l≈25 m under the columns and stiffening diaphragms of the building. The thickness of the slab is 1.0 m. The existing short continuous flight auger piles with a length of l≈15.5 m and a diameter of d=0.62 m, made for the previous project of the building, are also involved in the structural behavior of the new foundation.

The soil base is composed of Quaternary alluvial-deluvial deposits, loams and sands. The hydrogeological conditions of the site are described as having a high permanent aquifer level. No adverse physical and geological processes and phenomena within the site are observed.

Figure 1: General views of the construction project (2013 to 2015)

Figure 2: General views of the construction project (2020)

2. The automated instrumental monitoring system of the stress state for the soil base - combined piled raft foundation system

Twenty-three transducers of two types were installed at the construction site during the zero-cycle work as follows: strain meters, to determine the stresses in the bored pile shafts and in the upper and lower reinforcement grids for the raft slab, and soil pressure cells, installed under the bottom of the slab plate. The types of transducers and their location are given in Table 1.

Legend	Structure	Installation location	Type of transducer	Serial number
СТ-1	Pile d=1,500 mm СИ-3-1 (pile in the 12-Б axes)	Shaft upper section	Strain meter	404830
		Shaft middle section	Strain meter	404831
		Shaft lower section	Strain meter	404832
СТ-2	Pile d=1,000 mm СИ-3-2 (pile in the 14-Ж axes)	Shaft upper section	Strain meter	404847
ДДГ-1	Soil base in the 14-15 and Ж-И axes	Shaft middle section	Strain meter	404848
ДДГ-2	Soil base in the 15-16 and Ж-И axes	Shaft lower section	Strain meter	404845
ДДГ-1	Soil base in the 14-15 and Ж-И axes		Pressure Cell	329077
ДДГ-2	Soil base in the 15-16 and Ж-И axes		Pressure Cell	1332480
ДДГ-3	Soil base in the 16-17 and Ж-И axes		Pressure Cell	1332481

ТДН-1	Raft in the 15-Ж axes	Raft lower re-bars, along the alphabetical axes	Strain meter	404876
ТДН-2	Raft in the 16-Ж axes	Raft lower re-bars, along the alphabetical axes	Strain meter	404846
ТДВ-1	Raft in the 15-16 and Ж-И axes	Raft upper re-bars, along the alphabetical axes	Strain meter	404881
ТДВ-2	Raft in the 16-17 and Ж-И axes	Raft upper re-bars, along the alphabetical axes	Strain meter	404880
СТ-3	Pile d=620 mm in the Ж and 17-18 axes	Borehole upper section	Strain meter	404884
ТДН-3	Raft in the 17 axis in the Ж-И axes	Raft lower re-bars, along the alphabetical axes	Strain meter	404849
ДДГ-4	Soil base in the 20-21 and В-Г axes		Pressure Cell	329084
ДДГ-5	Soil base in the 21-Л axes		Pressure Cell	1332482
ДДГ-6	Soil base in the 20-21 and К axes		Pressure Cell	1332483
СТ-4	Pile d=620 mm in the 20-21 and В-Г axes	Shaft upper section	Strain meter	404882
СТ-5	Pile DIA=620 mm in the 20-Г axes	Shaft upper section	Strain meter	404878
ТДВ-3	Raft in the 17 and Ж-И axes	Raft upper re-bars, along the alphabetical axes	Strain meter	404877

Table 1: Types of transducers and their location

Figure 3 shows some common types of transducers and taking of initial readings.

Figure 3: Installing different types of transducers and taking initial readings

In general, the automated monitoring system has a classical multilevel structure:

- Level 1: 23 (twenty-three) transducers (strain meters and soil pressure cells). It provides data acquisition about the state of the project by means of analog signals.
- Level 2: two multiplexers (Type: BKC MUX 01.16.04). It provides multiplexing of analog signals from control and measuring equipment in a local data hub.

- Level 3: 1 (one) local data hub (Type: BKC LOCON RS/CL-01.008.02). It provides storage of readings of the control and measuring equipment in the memory of local data hubs with their subsequent transfer to the central data processing center.
- Level 4: 1 (one) central data center (Type: laptop). It provides collection and storage of data from the local hub with their subsequent processing in the Titan software. Level 4 hardware is a data collection server.

Figure 4 provides photographic evidence of some components of the automated monitoring system and the process of data collection to the central processing unit.

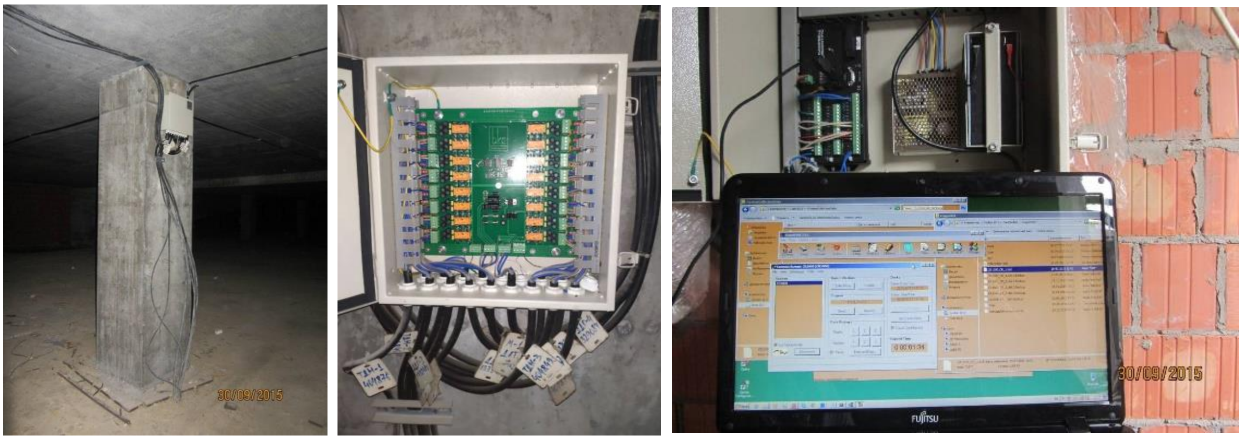

Figure 4: Some components of the automated monitoring system and the process of data collection

3. Simulating the base-foundation-structure system

To provide redundant calculations of the stress-strain state of the base-foundation-structure system according to architectural and design solutions, a 3D model was developed in the Revit software and calculations were performed in the Sofistik software using finite element method. Columns and piles were simulated with spatial bars; floors, walls, pylons and raft foundation were simulated with plate/shell elements.

The model of a finite width linear-deformed layer [6-7] was chosen as the model of the soil base for the most adequate interaction between the base and the large-size combined piled raft foundation. The boundary conditions in the plan for the soil mass are taken so that the impact of the rigid braced constraints of the mass is minimum.

The numerical calculation is performed using the finite element method, which is based on the elasticity theory solution, using the Sofistik calculation software for the first and second groups of the limit states. Calculations for the first group of the limit states include the calculation of the stress-strain state (SSS), which results in the determination of bending moments and transverse forces in the foundation slab. Calculations for the second group of the limit states include checking the strains of the base and the horizontal displacements of the framework.

Based on the selected parameters of the simulation model and the output data, the interaction between the construction project and the specified model of the base was simulated.

The base-foundation-structure analytical model from Revit (Fig. 5) was integrated into Sofistik. Figure 6 shows a deformed diagram of the building deformed due to its dead load in the software. The specific feature of simulating in the Sofistik software was the actual consideration of the soil resistance under the raft slab, which was obtained from the monitoring results: the resistance under the slab does not exceed the dead load of the raft slab (≈25 kPa), which indicates it is not involved in the behavior during the construction of the project.

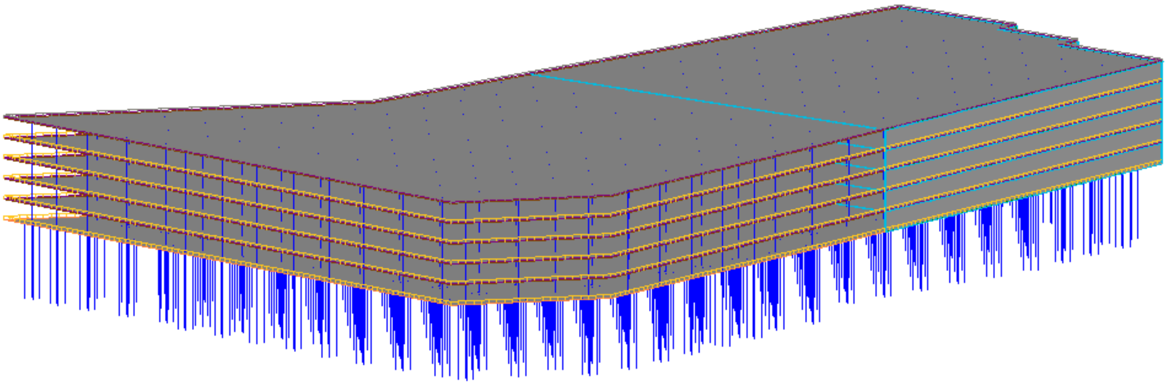

Figure 5: A base-foundation-structure 3D analytical model (Revit software)

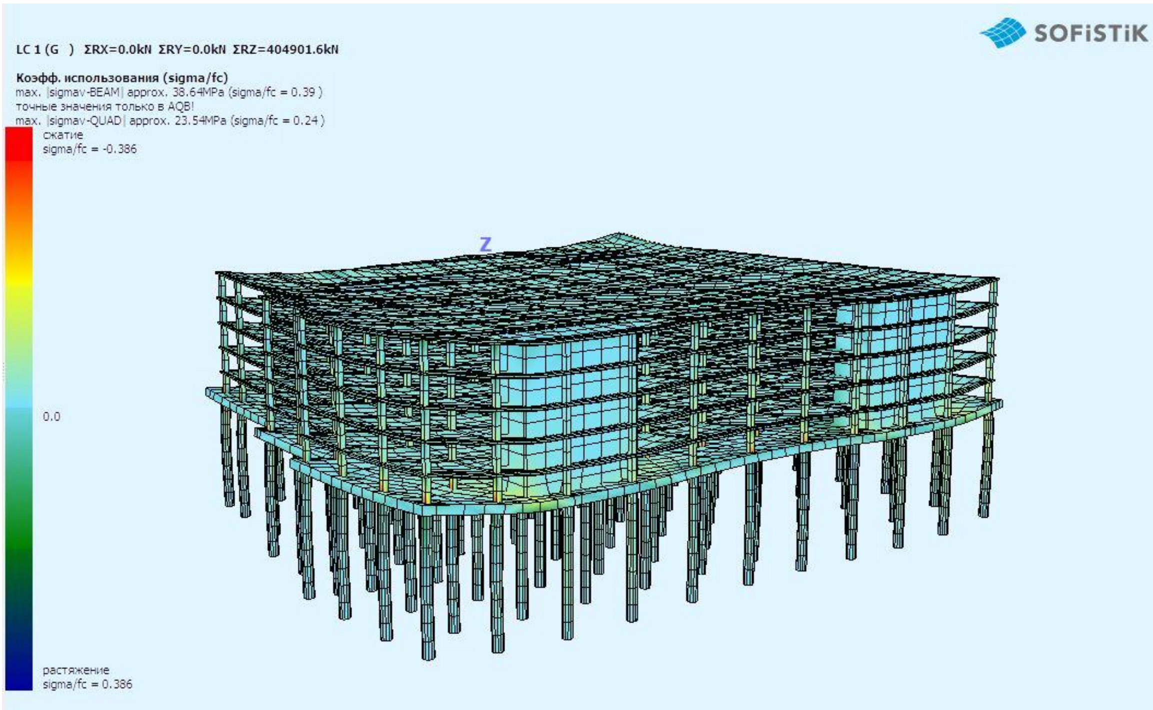

Figure 6: A deformed diagram of the finite element model (in the 14-21, В-Л axes) deformed due to its dead load (Sofistik software)

4. Comparison of the results of numerical calculations and instrumental monitoring

According to the last pickup of signals (March 2021) and their processing by the monitoring system using the Titan software, the calculated and actual force values in the elements of the combined piled raft foundation and its soil base were compared.

Table 2 and Figure 7 show the actual force values in the foundation structures and pressures on the soil base compared to the calculated ones. Furthermore, the calculated values obtained using the Sofistik software are given for the actual period of construction of the project (March 2021), i.e. when loading the soil base only with the full dead load of the building (moment elastic solution) without regard to the net and other loads and their calculated combinations.

Structure	Location	Measurement area	Forces in the structure acc. to the data from the monitoring system		Forces in the structure acc. to the calculated data using Sofistik	
			N, kN	M, kN·m/m	N, kN	M, kN·m/m
Pile d=1,000 mm	In the 14-Ж axes	Lower section	-78		-85	
		Middle section	-705		-723	
		Upper section	-1676		-1701	
Pile d=620 mm	In the Ж and 17-18 axes	Upper section	-525		-539.6	
Raft	In the 15-16 and Ж-И axes			65.1		67.5
	In the 16-17 and Ж-И axes			127.8		133.3
	In the 17 axis in the Ж-И axes			-209.7		-216.9
	In the Ж axis in the 17-18 axes			-304.3		-337.7
	In the 17-18 and И-К axes			37.3		40.3
	In the 15-Ж axes			239.4		245.7
	In the 16-Ж axes			277.7		283.6

Table 2: Comparative analysis of forces in the foundation structures

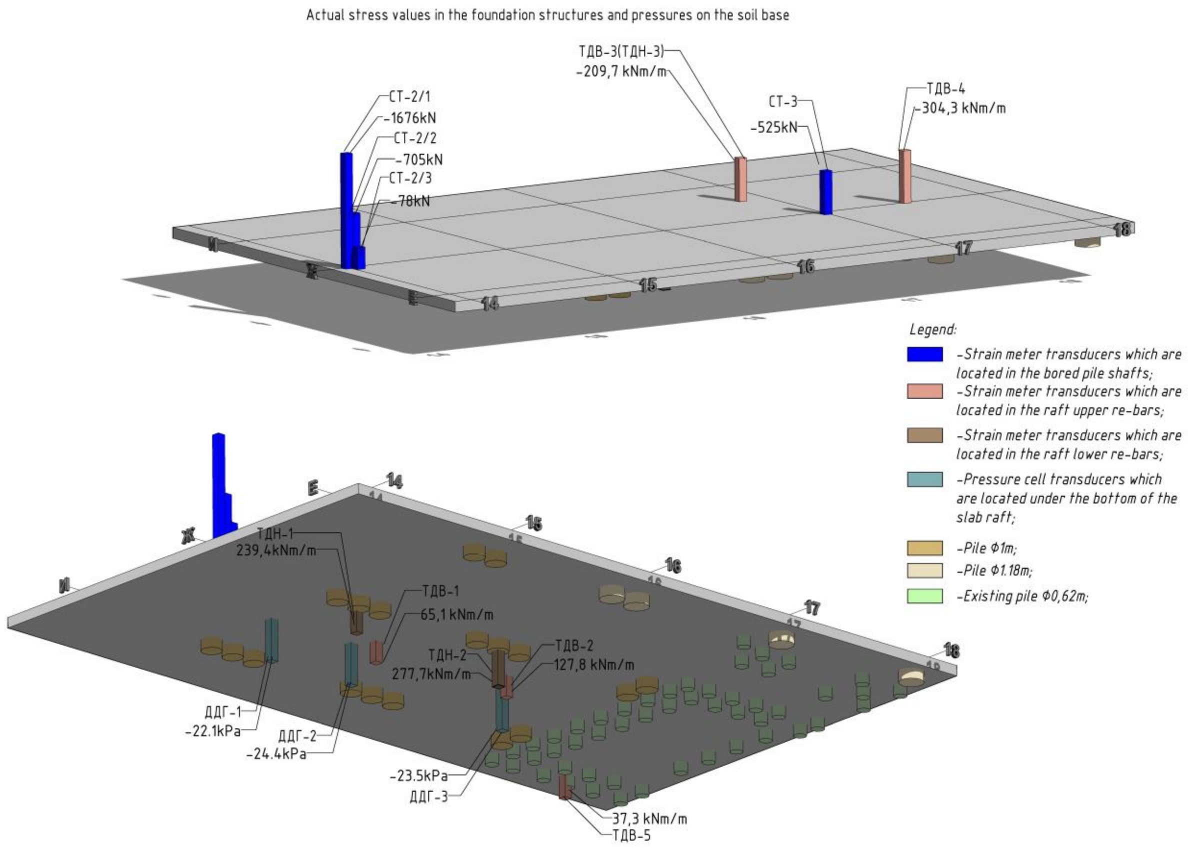

Figure 7: Actual stress values in the foundation structures and pressures on the soil base

Table 2 and Figure 7 show that the largest relative discrepancies are 9.9% for moment forces in the raft and 9% for longitudinal forces in the piles.

In our view, the most likely reasons for the discrepancies are:

- On the part of the monitoring system: The specific features of involving the transducers in the behavior, which are due to the sequence of erecting the structures and the behavior of the structure in real conditions;
- On the part of simulation in the Sofistik software package: a rough description of the structures and their interaction with the base.

5. Conclusions

Based on the results of the performed automated instrumental monitoring of the stress state of the soil base - piled raft foundation system of a construction project and their comparative analysis with the data of numerical calculations in the Sofistik software, the following conclusions can be drawn:

1. In general, there is qualitative and quantitative reproducibility of the estimated force values in reinforced concrete structures of a combined piled raft foundation.

2. The actual pressure under the bottom of the raft does not exceed the pressure from the dead load of the raft slab (≈25 kPa), which indicates that the raft slab is not involved in the behavior due to slight relative settlements of the combined piled raft foundation.

3. The obtained results of the field survey are indispensable scientific data required to justify the choice of the calculation model of the soil base and its parameters for adequate simulation of similar large-size combined piled raft foundations.

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