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The results of modeling the strain state of soil base reinforced by soil-cement elements under strip foundations of the building

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The results of complex experimental and theoretical researches of the deformed state of the system "soil-in-situ – soil-cement base – strip foundation – brick building" with layers of weak clay soils are given. By comparing the data of finite element method (FEM) modeling in a three-dimension task using an elastic-plastic soil model of the deformed state of the natural (with layers of weak clay deposits) and reinforced with vertical soil-cement elements (SCE) base of strip foundations of the five-section 9-10-story building, as well as the results of long-term (over 10 years) geodetic observations of this real object proved the correctness of using embedded beam pile elements to simulate SCE. The effectiveness of the SCE reinforcement method for improving soil bases with a low deformation modulus has been confirmed.

Keywords: poor-bearing soil, vertical soil-cement element, strip foundation, system «soil base – foundation – building», finite element method, deformed state, settlement

Результати моделювання деформованого стану армованої ґрунтоцементними елементами основи фундаментів будівлі

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Відзначено, що навіть за складних інженерно-геологічних умов майданчиків будівельні норми при проектуванні вимагають дотримання жорстких вимог щодо абсолютних і відносних осідань основ будівель і споруд. Наведено результати комплексних експериментально-теоретичних досліджень деформованого стану системи «природний масив – ґрунтоцементна основа – стрічковий фундамент – цегляна будівля» за наявності шарів слабких глинистих ґрунтів. Подано інформацію про дослідний майданчик, згідно якої в його геологічній будові до глибини 7 м беруть участь сучасні заплавні та руслові відклади, а до несприятливих фізико-геологічних процесів у його межах віднесені: підтоплення території; істотна неоднорідність ґрунтового масиву як за його площею, так і за глибиною; наявність слабких ґрунтів, сильнозаторфованої глини, несправжніх пливунів і т. ін. Порівнянням даних моделювання методом скінченних елементів (МСЕ) у просторовій (3D) постановці з використанням пружно-пластичної моделі ґрунту деформованого стану природної (з шарами слабких глинистих відкладів) й армованої вертикальними ґрунтоцементними елементами (ҐЦЕ) основи стрічкових фундаментів п'ятисекційної 9-10-поверхової будівлі, а також з результатами тривалих (понад 10 років) вимірів осідань цього натурного об'єкту доведено коректність застосування для імітації ҐЦЕ, так званих, пальових елементів embedded beam. Отримано задовільну збіжність між даними 3D моделювання МСЕ за удосконаленою методикою формування розрахункові схеми системи та тривалих натупних спостережень її деформацій. Описано особливості складання розрахункової схеми системи «основа – фундамент – будівля», принципи призначення її геометричних розмірів, вихідних даних, передумови та параметри чисельних розрахунків, послідовність етапів моделювання, вибір моделі поведінки ґрунту. Підтверджено ефективність методу армування основи ҐЦЕ для поліпшення основ, складених з ґрунтів з низьким модулем деформації.

Ключові слова: слабкий ґрунт, вертикальний ґрунтоцементний елемент, стрічковий фундамент, система «основа – фундамент – будівля», метод скінченних елементів, деформований стан, осідання

Introduction

About 80% of the territory of Ukraine is characterized by difficult engineering and geological conditions for the construction of buildings and structures: loess subsidence, weak soils (including silt, peat, and peaty sediments), swelling, filled and alluvial soils, flooded areas, as well as areas with dense construction, etc.

However, at the same time, both European [1] and Ukrainian [2] modern building regulations quite reasonably require strict compliance with strict requirements for absolute and relative settlements of similar foundations of buildings and structures during design.

Review of the research sources and publications

Therefore, under the above-described conditions in modern geotechnics [3–7] the concept of analyzing the deformations of the foundations of buildings or structures not separately, but rather the assessment of the stress-strain state (SSS) of the “soil base – foundation – building” system is usually tested, after which the characteristics of its components are improved.

Also, geotechnical practice [8–16] has proven that one of the most effective methods of creating reliable artificial foundations is the method of reinforcing weak soil-in-situ with soil-cement (most often vertical) elements (SCE), which are created using drilling technology. As a result, the bearing capacity increases and the deformability of natural bases decreases. Soil-cement bases of buildings and structures are effective even in the presence of weak soils (floodplain, loess, man-made, etc.) with a thickness of up to 30 m.

It is appropriate to note the results of parallel field experiments and numerical modeling by the finite element method (FEM) in a spatial (3D) and flat (2D) settings, which confirmed a significant improvement in the mechanical properties of weak clay foundations after their reinforcement with vertical SCE [13, 14].

In the development of these researches, the authors of [16] also conducted tray punch tests and determined new empirical dependences of strength and deformability of the base on the density of the soil skeleton, depth of GCE, percentage of reinforcement, etc.

For the correct evaluation of the SSS of the systems "soil-in-situ – soil-cement base – foundation – building" created in this way, it is advisable to use modern geotechnical software products of 2D or 3D simulation of FEM with an elastic-plastic soil model [17–19]. These software complexes (SCs) have enough functions that allow specialists to perform such calculations of buildings on foundations strengthened by SCE.

However, as proven by geotechnical practice, the most reliable criterion for the reliability of structural and technological solutions and the correctness of their calculation methods are long-term geodetic observations of deformations (settlement, tilting) of buildings and structures [20, 21].

Definition of unsolved aspects of the problem

At the same time, in order to improve the regulatory framework for the project engineering of soil-cement bases of buildings and structures under conditions of weak soils, a sufficient volume of complex experimental and theoretical soil bases research of SSS of strip foundations reinforced with vertical SCE has not yet been formed.

Problem statement

Therefore, the purpose of this work is comprehensive experimental and theoretical research of the deformed state of the system "soil-in-situ – soil-cement base – strip foundation – brick building" in the presence of layers of weak clay soils.

Basic material and results

So, in order to achieve the set goal, the following tasks were solved:

– investigate the development of deformations in the case of construction of the building on a natural (unreinforced) soil base with the presence of layers of weak clay soils by FEM 3D modeling using an elastic-plastic soil model;

– assess the development of deformations of the soil base reinforced with vertical SCE by FEM 3D modeling using an elastic-plastic soil model;

– compare the SSS of the reinforced and natural soil base of the strip foundations of the building according to the FEM calculation with the data of long-term geodetic observations of the same object.

An experimental five-section residential building (Fig. 1) with built-in premises on the first floor is located in the city of Poltava on the street Panianka, 65B. The building is complex in plan, 9-10 stories high, with longitudinal and transverse load-bearing brick walls, ceilings made of round hollow panels with monolithic sections.

Figure 1 – General view of the experimental object at the end of the construction of the last section, 2012

In fact, this building is located on two parts of the site with different layers of soils. Particularly difficult engineering and geological conditions are characteristic of the massif under sections IV and V, where clay is heavy, flowable, heavily peated.

Previously, the site was partially built up with one-story outbuildings. The surrounding old buildings have clearly visible cracks, the cause of which, in most cases, are uneven deformations of the bases of their foundations.

The geological structure of the site up to a depth of 7 m includes a modern floodplain and channel sediments of the river Vorskla. In particular, the site is composed of sandy and clay deposits of the Quaternary age, which are overlain by bulk soils with a thickness of up to 2.7 m.

The relief of the building site is flat, significantly changed by human activity. The difference in ground surface markings within the site does not exceed 0.5 m. At the time of the search, the groundwater level was 2.3-2.5 m from the ground surface of the site.

Adverse physical and geological processes and phenomena within the area include are following:

– the site is flooded;

– significant thickness of bulk soils (up to 2.7 m);

– significant heterogeneity of the soil massif both in terms of its area and depth (for example, there are numerous lenses and layers of dusty sand and plastic sand);

– clays (soil layers 2-4) belong to the weak (the deformation modulus is less than 5 MPa);

– heavy, flowable clay (soil layer 3) contains more than 40% of organic substances, i.e. it belongs to strongly peated clay;

– dusty sand, with organic impurities (soil layer 5) belongs to non-genuine floating sand.

The foundations of the building are strips, made of monolithic reinforced concrete. The height of the foundation tape is 0.5 m.

The base is reinforced with vertical SCE using drilling technology with a diameter of 500 mm and a length of 2300 mm. A buffer layer of crushed stone is created on top of this soil-cement base.

In Fig. 2 shows several stages of construction of SCE, foundation and building structures: fig. 2a – arrangement of the SCE in pits for sections I and II; fig. 2b – drilling rig in pits for sections III – V; fig. 2c – arrangement of crushed stone buffer layer and strip reinforced concrete foundations for sections III – V; fig. 2d – floor construction of sections I and II. By the way, the first section of the building was commissioned in 2012 and the last in 2013.

Table 1 shows the values of the physical and mechanical characteristics of the soil layers of the massif of the experimental object.

SC Plaxis 3D Foundation, which has been sufficiently tested for solving a number of geotechnical problems, was used to simulate FEM in a three-dimensional problem using the elastic-plastic soil model of the SSS system "soil-in-situ – soil-cement base – strip foundation – brick building" in the engineering and geological conditions of the construction site.

The three-dimensional model of the experimental object (its building structures) is presented in fig. 3. The geometric model is a composition of boreholes that are created according to the engineering and geological sections according to the technical report before the start of construction.

The dimensions of the calculation area of the problem are determined based on the following considerations:

– the lower horizontal limit is located in the last layer of the engineering-geological section with a margin (see Table 1);

– lateral vertical boundaries are accepted at a sufficient distance from the zone of SSS determination in all directions;

– the upper limit corresponds to the planning surface.

Thus, the dimensions of the calculated area in the plan are 100×100 m. The depth of the specified area is accepted with a certain margin and is equal to 40 m. Soil stratification is given according to the data of exploratory wells. The parameters of each layer of the calculation area were set according to the data in the table. 1.

Figure 2 – Characteristic stages of building construction:
a – arrangement of SCE in pits for sections I and II;
b – drilling rig in pits for sections III-V;
c – arrangement of crushed stone buffer layer and strip reinforced concrete foundations for sections III-V;
d – floor construction of sections I and II

Table 1 – Geotechnical characteristics of site`s soils layers of the experimental object

Soil layer	A brief description of the soil layer	ρ, g/sm^3	I_L	I_P	W	Sr	e	$φ_1$, °	$φ_2$, °	c_1, kPa	c_2, MPa	E, MPa
1	Loose soil	1,50	>1	0,15	0,38	-	-	-	-	-	-	-
2	Clay, light dusty, rigid, with organic impurities	1,81	0,26	0,22	0,30	0,86	0,92	11	13	23	25	1,5
3	Clay is heavy, fluid, heavily peated	1,31	>1	0,62	1,55	1,00	4,15	3	4	3	5	0,5
4	Clay, light dusty, soft-plastic, with organic impurities	1,89	0,53	0,19	0,31	0,97	0,86	13	15	22	33	1,5
5	Sand with organic impurities, dusty, medium density, saturated with water, with lenses and layers of sand	1,92	-	-	0,27	0,95	0,74	20	23	1	2	6,5
6	Shallow sand with numerous layers and lenses, medium density, saturated with water	1,97	-	-	0,26	0,99	0,69	23	26	2	3	10
7	Shallow sand, heterogeneous, dense, saturated with water	2,00	-	-	0,22	1,00	0,69	24	26	2	3	33
8	Dusty, semi-hard, thin-layered, glauconite loam	1,85	0,31	0,16	0,25	0,84	0,79	16,5	19	15	23	16,5

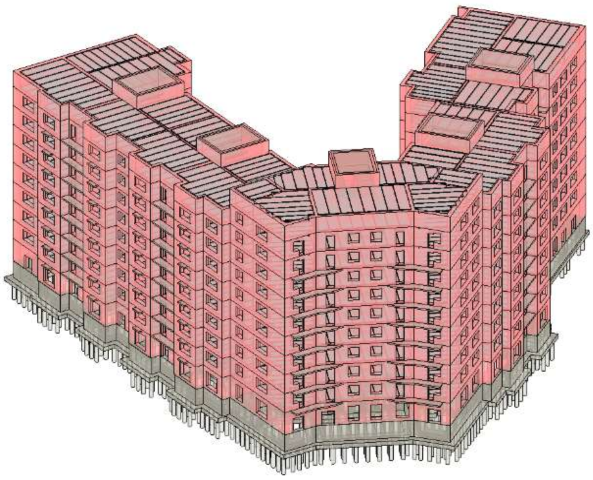

Figure 3 – 3D model of the experimental object (only structures without external finish)

A mesh of finite elements was created, for which the accepted level of coarse density is set due to a significant number of soil layers, the presence of SCE, the complex shape of the building and, therefore, a large number of generated finite elements, the calculation scheme is shown in Fig. 4.

The SCE were modeled with pile elements called embedded beams. The type of behavior is a pile, the connection with the foundation is free, the behavior of the material is linear elastic.

The selected element type and material behavior are due to the fact that for problems of such a volume, the use of volumetric elements in such a quantity leads to a significant increase in calculation time, an increase in the number of non-connections and, based on the above, "calculation collapse".

The magnitude of the deformation modulus of soil-cement is taken to be equal to 300 MPa based on previous studies of the scientific school of geotechnics of the National University «Yuri Kondratyuk Poltava Polytechnic» [10, 13, 15] since there is no information on the selection of samples from SCE to determine the mechanical characteristics of soil-cement on this object. The specific gravity of soil-cement is 20 kN/m^3 and its Poisson ratio is 0.25.

The parameters required to specify the element as pile axial skin resistance and base resistance are calculated according to regulatory documents [1] as for bored piles for each section separately based on the location of the boreholes.

The correctness of this approach is described in the authors' materials [14, 16, 20]. The total number of SCE for creating an artificial base in the project was 843 units.

All strip foundations (according to project data) and basement walls from foundation blocks are also modeled.

The above-ground part of the building was considered as a load at the level of the top of the basement walls.

The values of the physical and mechanical characteristics of reinforced concrete walls and foundations were taken as for C20/25 class concrete.

The initial data used in the calculations include:

– coordinates of nodes of the mesh of finite elements;

– description of loads (magnitude, direction, point of application);

– description of finite elements (node numbers; strength characteristics, deformation modulus, Poisson's ratio, etc.).

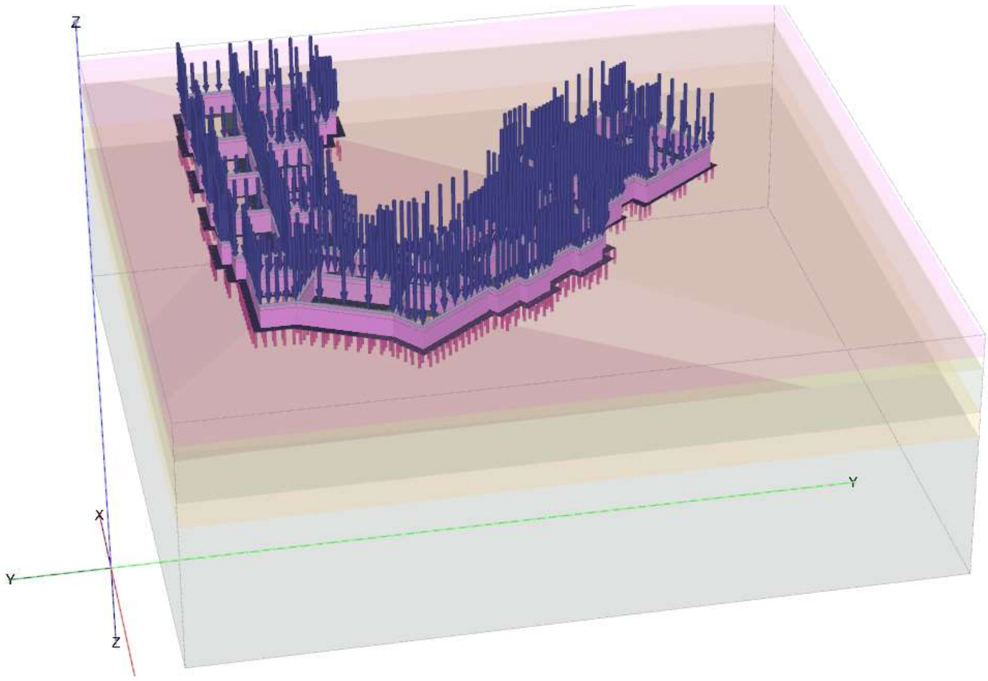

Figure 4 – General view of the calculation model of the system «natural soil base – reinforced soil-cement base – strip foundation – brick building»

The construction process of this object is modeled in 4 phases:

– initial (calculation type – gravity loading), on which the massif received certain deformations under its own weight in accordance with the consequences of soil extraction;

– the stage of soil excavation (setting up the pit);

– arrangement of the foundation tape and basement walls below the first-floor mark;

– application of loads from the above-ground part of the building.

In the calculations, the following prerequisites and parameters are adopted. The iterative procedure provided for: relative error equal to 0.1; the maximum number of iterations does not exceed 60; the maximum number of steps in each phase is 100. After completing the calculations of all phases, the predicted limit state was reached.

The soil behavior model is the Mohr-Coulomb elastic-plastic model. This easy-to-use nonlinear model relies on soil parameters that are known in most practical geotechnical problems. In particular, this model is well tested in the calculations [17–19] of the real bearing capacity and destructive loads on the foundation along with other problems where the behavior of the soil during destruction has a decisive role. FEM modeling was performed in a 3D task using an elastic-plastic soil model of two different systems:

– «natural soil base – strip foundation – brick building»;

– «natural soil base – reinforced soil-cement base – strip foundation – brick building».

In fig. 5 and fig. 6, respectively, we show the results of modeling the settlements of the natural (unreinforced) and artificial (reinforced by vertical SCE) base of strip foundations of the building.

To assess the reliability of the data obtained by 3D modeling in fig. 7 shows the results of long-term geodetic observations of the wall marks of the building. In particular, it was recorded that according to the current state, the smallest subsidence of the I-II sections was 187 mm, the average was 210 mm and the largest was 226 mm. Similar results were obtained for site III, respectively, 235 mm, 245 mm and 256 mm; for section IV – 248 mm, 254 mm and 264 mm; for cross-section V – 248 mm, 256 mm and 263 mm. In the table 2 compares the amounts of subsidence of the foundations of the sections according to modeling data and long-term geodetic observations.

Table 2 – Comparison of data of 3D FEM simulation and geodetic observations of settlements of the strip foundations of the object

Section	FEM modeling, mm		Long-term geodetic observations, mm
	Natural base	Reinforced base	
I	183…285	185…286	187…215
II	230…321	236…324	215…256
III	253…328	255…327	235…251
IV	273…368	272…358	248…264
V	315…430	268…377	249…260

Simulation results in table 2 correspond to the foundations of the external walls (the actual location of the wall marks). The measured settlements of the soil bases of the building sections and obtained by FEM Plaxis 3D simulation have a satisfactory convergence.

Cracks and other visible deformations have not been recorded for almost 10 years of observations.

Figure 5 – Results of 3D FEM modeling of the unreinforced base of the foundation strip (settlements in mm)

Figure 6 – Results of 3D FEM modeling of the reinforced base of the foundation strip (settlements in mm)

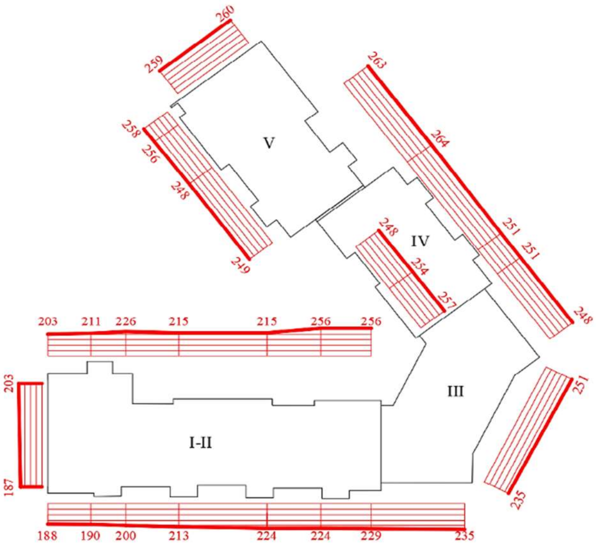

Figure 7 - The results of settlements according to long-term geodetic observations of the object

Conclusions

Therefore, by comparing the data of 3D FEM modeling simulation using an elastic-plastic model of the soil of the stress-strain state of the natural soil base (with layers of weak clay deposits) and reinforced soil base with vertical SCE of strip foundations of a five-section 9-10-story building as well as with the results of long-term settlement measurements of this the object is set as follows.

1. The correctness of the modeling results with software Plaxis 3D when applying the Mohr-Coulomb elastic-plastic model for the analysis of the deformed state of the system «natural soil base – reinforced soil-cement base – strip foundation – brick building» has been proven, in particular, with the use of pile elements «embedded beam» for modeling SCE.

2. Satisfactory convergence was obtained between the data of 3D FEM simulation based on the improved method of forming the calculation scheme of the system and long-term geodetic observations of its deformations.

3. The effectiveness of the vertical SCE soil bases reinforcement method for improving foundations on site with soil layers that have low deformation modulus has been confirmed.

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